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ABSTRACT

The two essays in this monograph are intended to clarify the main problems of research in graphic communication. The first essay summarizes research concerning the effective use of graphic devices in texts and other instructional materials. Following a brief discussion of the technical terminology of graphic communication, the essay reviews research in the areas of visual perception, presenting quantitative data, scientific and technical diagrams, algorithms, cartology, notations, comic strips, and typography. The second essay reviews research on the presentation of quantitative data in texts. Research reviewed deals specifically with methods used to present general aspects of data and methods of presenting exact numerical data. (FL)

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Research in graphic communication

Graphics in text [S]
How numbers are shown

Michael Macdonald-Ross

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IET monograph no 7

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PREFACE

For some time now I have been working on the problems of graphic communication. Some fruits of this work are now published: first as a bibliography (IET Monograph No. 6), now as two long reviews. The full references to these reviews are:

MACDONALD-ROSS M. Graphics in Texts. In L.S. Shulman (ed) Review of Research in Education (vol. 5) Itasca, Ill.: Peacock, 1977

MACDONALD-ROSS M. How Numbers are Shown: a review of research on the presentation of quantitative data in texts. Audio-Visual Communication Review, 1977, 25, 359-409

Both these issues were actually published in 1978, although bearing the date 1977; for the sake of simplicity it seems best to use the earlier date when referring to either paper. As it happened, no offprints were available for either of these reviews so, as they are part of the same research programme, I have reprinted them together in this monograph.

Although I started off with the simple-minded idea of summarising previous research, this has long since given way to a much more important objective. My aim in these reviews has been to clarify the main problems of research into graphic communication. In other words I have concentrated as much on the methodology of research as on its results. Throughout this work I have avoided any mechanical assessment; there are no arithmetical summaries for and against because this presupposes all research to be of equal merit, which is obviously nonsense. In developing criteria for deciding which research should be given preference I have been able to uncover some principles of enquiry which seem to be of importance and general scope. In general, these papers should be seen as first steps along the road to productive research and not (as they might seem at a first glance) the coping-stone of a finished monument.

Where the research seems valid and reliable I have summarised it so that practitioners can get some idea of where to look for helpful advice. However, no-one should imagine that the task of converting these research ideas into practice is simple. It is a creative act at least as important and as difficult as the original research itself. I should also enter a caveat against any simple notions of 'media'. At first sight a printed text seems quite different from a television programme, a film or a conversation in the street. However, I believe that there are basic principles of human communication which underlie all these superficially different circumstances of interaction. Therefore, this work needs to be underpinned by an adequate theory of human communication. There is no such theory at the moment, despite the claims of certain academic groups (whose merits I need not discuss here). Nevertheless it is as well to remember that there is no really progressive scientific research without the underpinning of adequate theory and conceptual apparatus. One of the most serious obstacles to progress at present may be the continual assumption that important

practical problems can be solved by practical means without any recourse to theory. The whole history of science speaks loudly against that kind of over-simple pragmatic assumption. On the other hand it would be a foolish researcher who did not look very closely and carefully at the objects of his research. In fact, as Konrad Lorenz says in the extract below, careful observation is the starting-point of science.

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We are living in a time in which it has become fashionable to assess the 'exactitude', and with it, the value, of any scientific result exclusively by the degree to which quantifying methods took part in obtaining it. This opinion is one of the dangerous half-truths which fashion is all too prone to accept. While it is entirely true that quantification invariably has the last word on *verifying* the correctness of any scientific statement, it is a fundamental error to assume that knowledge can progress on the basis of quantification alone. The current overrating of quantification as a source of knowledge has very serious epistemological consequences. The first and worst is that it leads to contempt of observation pure and simple which, as I am going to show, undeniably is the basis of all inductive science. The depreciation of observation has gone so far that the term 'naturalistic', as applied to scientific work, has assumed, with some behaviouristic psychologists, a definitely derogatory connotation. Another highly dangerous consequence of overrating the importance of quantification lies in forcing the several branches of inductive science into an entirely unnatural and unjust scale of values, in which physics, particularly atomic physics, not only range first, but are regarded as the paragon and only genuine representative of a 'science' while, on the other hand, those branches of inductive research which are chiefly occupied with the description of structures, are entirely beneath contempt.

It is easy to demonstrate the fallacy of this attitude, which, incidentally, is by no means that of atomic physicists. What concerns us first is that the derogation of structure as such leads to despising all cognitive functions which convey to our knowledge the existence and the special configuration of structure. This again leads to *atomism*, which can be defined as the erroneous belief that natural laws prevailing in matter can be explained on the basis of more general laws of nature without taking into consideration the way in which the matter in question is structured.[88] Not even the simple lawfulness of the functioning of a clock, for instance the 'law' that the big hand moves twelve times faster than the little one, can ever be understood without a preceding morphological, in other words *descriptive*, study of the clock's structure in general and the relative numbers of cogs on certain cogwheels in particular.

Extract from Konrad Lorenz 'Studies in Animal & Human Behaviour II'
Methuen 1971 p 246-7

2

Graphics in Texts

Michael Macdonald-Ross
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> To the scientific mind it is most annoying to have to deal with phenomena that cannot be formulated in a way that is satisfactory to intellect and logic.
>
> *Carl Jung*

INTRODUCTION

The purpose of this review is to summarize what is known about the effective use of graphic devices in texts and other instructional materials. Information about graphic devices comes mainly from two sources: the experience of skilled graphic communicators and the formal laboratory experiments of applied psychologists. Both these sources have been consulted for this review. To keep it to a reasonable length I discuss what I think are the central issues and leave other questions untouched. It may be useful for researchers to consult the recent bibliography by Macdonald-Ross and Smith (1977), which lists all the relevant research known to me as I write this review.

Graphic devices have been invented by humans to help represent, explain, and control the world in which they live. Ordinary language (verbal and gestural) is our primary means of communication, but there are many tasks for which it is ill-suited. We cannot do without mathematical and musical notations, scientific diagrams, tables, and maps. Some such systems of representation are essential to us, as they have been to all civilized cultures since

LAWRENCE T. FRASE, National Institute of Education, and GEORGE R. KLARE, Ohio University, were the editorial consultants for this chapter.

I would like to thank Professor Brian Lewis and Dr. Tom Sticht for their helpful suggestions.

the first city-states. The relationship between language and graphics is complex and subtle; it deserves much more attention from scholars than it has so far received. Gombrich (1972) has spelled out some of the basic issues, and the broad history of graphic communication is given in Hogben (1949).

The first sentence of this review introduced some key terms that need clarification: *texts, graphic devices,* and *effective use.* A text is a printed or written book or document: marks on paper. The interest lies in what is being said (the content), how it is interpreted and used by readers, and how the organization of the content affects the reader. Thus this review deals with a matter of great general interest (how we communicate information to each other) in a special setting (the printed text and its reader). Much of the review also applies, with certain qualifications, to other media such as film, television, and computer graphics, though these connections will not be spelled out explicitly.

The term *graphics* is not exact, but it is still the best word to describe alternatives to prose. In this review *graphics* is meant to exclude ordinary language and its derivatives (such as poetry and Basic English). Also this review does not deal with decorative illustration, fine art, or advertisements. Many of the graphic devices dealt with here are pleasing to the eye, and no doubt this does help to attract attention and motivate the reader. However, the prime purpose of the devices discussed is to display conceptual information: numerical, logical, spatial, and temporal data. There is a world of culture that has been left out of this review, especially the classic arts of the book illustrator (Beardsley, 1893, and Rackham, 1911, are two superb examples; Bland, 1958, is a standard history of book illustration), and newspaper and magazine advertisements and wall posters. Comic strips are mentioned briefly, but the space accorded them scarcely does justice to their cultural significance. The body of the review deals with those graphs, charts, diagrams, notations, and other devices which are specially adapted for presenting scientific, technical, social, and commercial information.

The term *graphic device* refers to a particular diagram; the term *graphic format* refers to a family of devices, such as Cartesian graphs. The phrase *system of representation* refers to the context and rules of procedure associated with a graphic format: not just the marks on paper, but also the rules for construction and interpretation (whether explicit or implicit). Such rules include ways to decide whether a particular subject matter can be represented legitimately by a particular format. The area of legitimate use of a format is its *domain.* These brief definitions need further development; for example, the status of language associated with graphic devices has not been spelled out. Also, it should be noted that some graphic formats make use of more than one system of representation. These subtleties would need teasing out in any comprehensive theory of graphic communication.

The third key term to be clarified is *effective use.* Since the decorative

connotations of graphics are considered here in a secondary role, fairly strong criteria of effectiveness can be adopted. For some graphic formats a straightforward behavioral definition will do: The device is effective if and only if the user can perform some well-specified operation with its aid. Nomograms and algorithms are two such cases. Other formats aim at comprehension; the reader is meant to see general trends and relationships. Many scientific diagrams and tables of social statistics are of this type. In some cases the format is strongly directive (algorithms; Isotypes), but other formats allow the reader to interpret or use them in different ways (many maps and tables). This state of affairs is depicted in the simple 2 X 2 table presented as Table 1.

The test-items corresponding to the four cells, I, II, III, and IV, in Table 1, would have these characteristics:

Cell I. Items of high validity derived from task analysis; all items to be attempted by subjects; criterion test with pass mark set at an appropriately exacting level.

Cell II. Same as cell I, but subjects attempt only those items that are relevant to their purpose.

Cell III. Items of lower validity derived from experts; all items to be attempted by subjects; if criterion-based, pass level may be lower than in cells I and II; may be marked competitively in some cases.

Cell IV. Same as cell III, but subjects attempt only items relevant to their purpose.

Experimenters often try to raise the reliability of items in cells III and IV by setting rote-recall tasks. This seems unwise, for it makes it difficult to draw general inferences which would be useful in practical situations. It is worth remembering that the most usual purpose of graphic devices in cells III and IV is to display some general trend or other relationship; exact recall of numerical or other data is rarely required. This problem is familiar to those who construct comprehension tests in education: the tradeoffs between reliability and content validity are difficult to handle. To summarize: in some

TABLE 1
A Simple 2 X 2 Classification of Test Items

		AIMS: Tasks	AIMS: Comprehension
Control: Directive		I	III
Control: Reader selects		II	IV

cases the effectiveness of a graphic device can be tested rigorously and the results interpreted unambiguously (cells I and II), whereas in other cases the question of effectiveness may be less easy to decide (cells III and IV). This is important for the design of experiments and their interpretation by the practitioner.

The empirical studies to be discussed in this review have been tested against a severe criterion: Can practical communicators use the results, and can other researchers build upon them? These demands are met if work is directed toward a relevant question, valid in design and execution, properly reported, and robust when applied in the field. Since many experiments fail one or more of these tests, some work which others have taken at face value does get more skeptical treatment in this review.

The review also makes use of the tacit skills of expert graphic communicators, which constitute a valuable reservoir of prescientific knowledge. I have discussed the ideas in this review with many applied psychologists and graphic designers. It seems some psychologists believe that the only reliable source of knowledge is the controlled laboratory experiment, while designers often reject the idea of systematic empirical testing. However, it may be more useful to see these two traditions as complementary (see comments in Macdonald-Ross, 1977, Macdonald-Ross & Smith, 1977, and Macdonald-Ross & Waller, 1975a). An understanding of the practical art of graphic design can guide the researcher toward fruitful experiments and away from certain kinds of costly mistakes. The designer also has much to gain from empirical research; too often he fails to get usable feedback about the effect of his work, and he may unwittingly copy the bad practices of other designers.

According to certain books on methodology, one tests to eliminate false hypotheses but this does presuppose that one has grounds for generating the hypotheses in the first place. At this stage in the progress of graphic communication it is no easy matter to decide which hypotheses are crucial, or even to decide what the key variables are in a graphic device. Perhaps a more cogent reason for conducting tests is to *externalize* the hitherto tacit know-how of the acknowledged expert (the master performer) so that it can be talked about, criticized, and improved.

VISUAL PERCEPTION

> Percepts are guesses.
> *Gregory*

Research into visual perception has a long and distinguished history, so it is not unreasonable to hope that the results might be of some use to practising graphic designers. In an effort to cover such a broad field it is useful to make two simple distinctions. One can choose to look mainly at the established

results of a science or at the *methods* of that science. Furthermore, one can look at the most *general* or universal aspect of a science or at its *particular* aspects.

These distinctions must be used with some circumspection, for a particular world-view will condition the researcher's choice of problem, and often it will determine the methods used to tackle the problem. Provided this is borne in mind, we can say that research into visual perception can contribute to the practice of instruction by providing for:

1*a*. Universal prescriptions based on the results.
1*b*. Particular prescriptions based on results of research into limited problems.
2*a*. General research methods useful for a wide range of problems.
2*b*. Special-purpose research methods for the solution of particular problems.

Universal Prescriptions

Under category 1*a* the work of Abercrombie (1960), Fleming (1970), and Travers (1970) should be noted. Abercrombie used Gestalt theory as the basis for a series of seminars designed to help medical students with their learning problems. These problems included both perceptual learning (e.g., diagnosing X-rays) and conceptual learning (e.g., meaning of key terms in clinical medicine). Abercrombie's book is full of examples taken from these seminars, with edited transcripts of the group discussions. It is the work of an inspired teacher. Nevertheless, we must ask an interesting question: Did this teacher's seminars derive from the prescriptive force of Gestalt psychology, or did they come from her experience and intuition, with the framework of theory added as a post hoc justification?

The book-length review by Travers (1970) covers in detail the contribution made by Shannon's information theory (Shannon & Weaver, 1949) to our knowledge of the human perceptual system. This is a valuable survey, but despite its subtitle—*A Primer for Media Specialists and Educational Technologists*—it is by no means clear how practitioners can use this knowledge. Take as one example the work on sensory channel capacity, which is one of the more fruitful contributions of information theory to psychology. In order to make use of information theory experiments must be designed to allow fairly rigorous quantitative inferences to be drawn. To achieve this end it is essential to eliminate the effects of prior knowledge and experience; hence the use of letters, numbers, and nonsense syllables as the raw "information." The experimenter's justification is the reasonable hope that the ultimate limits of channel capacity cannot be transcended, and these methods will discover those limits.

The trouble with this reasoning is that the notion of information is being

used with two meanings (Weaver recognised this; see his discussion of three levels of communication in Shannon and Weaver, 1949; see also Green & Courtis, 1966; Johnson & Klare, 1961). No one doubts that there is a limit to the rate of transmission of nerve impulses and a limit to the rate these impulses can be decoded by the cortex. However, there is a huge difference in the significance of such a message according to the set and prior knowledge of the individual subjects. This commonsense observation was brought home with great force by the work of de Groot (1965, 1966) and is put thus by Simon (1969): "We now know that meaningfulness is a variable of great importance." Similar problems arise with the work on short-term memory, since the concept of "chunk" is so embarrassingly dependent on the subject's prior experience of the problem domain.

For our purposes, however, it is not necessary to reach any definite conclusions about the information-theoretic approach to perception research. It is sufficient to recognize that translation of the results into prescriptions is a nontrivial task which is fraught with pitfalls and difficulties. Is it reasonable to expect practical communicators to make that translation? I suspect not, and so does Travers, who cautions the reader not to expect to "receive the kind of help that research rarely can give." In Travers's opinion, basic research can give these benefits to the practitioner:

1. Provide a *vocabulary* so that practical problems can be discussed with more precision.
2. Enable the practitioner to *think more intelligently* about the problems he encounters.

Of course, a technical framework biases the way problems are selected and interpreted—with great benefit if the framework is appropriate, and with much wasted effort if it turns out to be inappropriate.

Fleming's Detailed Review. Fleming (1970) gives a detailed review of perception research and provides advice for the designers of instructional materials. This valuable source includes 61 research findings in eight chapters—a huge body of advice. Some issues are selected for comment below, though it is essential for serious students to consult the original review for detailed references.

Fleming's first chapter ("Man as Perceiver") covers these principles:

1. Man's perception is relative.
2. Man's perception is selective, organized, and influenced by set.
3. Stable individual differences in perception do exist.

In general, people do not perceive absolutes. However, our perceptual system is especially well adapted to making comparisons and distinctions. Such comparisons can be *explicit* (presented together side by side, as in Isotype charts) or *implicit* (the learner compares new knowledge with a similar situa-

tion drawn from memory). This is a good example of researchers and practitioners reaching the same solution independently, which naturally increases our confidence in the conclusion. The Isotype system is discussed later, but it is worth summarizing here Otto Neurath's central ideas on visual communication:

1. All visual communication is based on comparisons.
2. A visual statement is an explicit visual comparison.
3. A visual argument is a set of comparisons selected to make a teaching point.

These ideas are completely consistent with Fleming's first principle, though they were not derived from formal experiments in perception. Fleming's second and third principles are well treated in the standard textbooks, and they are made specific for the designer by Fleming in later chapters.

Fleming's second chapter ("Attention and Preattention") tackles an important subject, but the author runs into some difficult problems. "Man's attention is drawn to what is novel" is certainly true in some sense, but there is an apparent conflict with a previous principle, "Man perceives what he expects." Also, "Man's attention is drawn and held by complexity" runs counter to "The organization of a stimulus markedly influences the speed and accuracy of perception." I do not think Fleming succeeds in resolving these problems, and I am also not impressed by Vernon's solution: "In directing his attention, man seeks a balance between novelty and familiarity, between complexity and simplicity, between uncertainty and certainty" (Fleming's summary of Vernon, 1952).

The notion of "balance" used here by Vernon is, I suggest, a nonexplanation. People do attend sometimes to the novel and sometimes to the familiar; but apparently we do not have at present a satisfactory account of these differences in behavior. To get to the bottom of questions like this researchers should test not universal (yes/no) hypotheses but more limited when/when not questions. The practitioner needs to know *in what situations* a particular method is appropriate. Lacking such information, Fleming partially retrieves the situation with common sense: "Change or novelty should direct attention to the most relevant ideas in a message rather than the marginal or superficial."

Fleming's third and fourth chapters ("Perceptual Elements and Processing" and "Perception of Objects, Pictures and Words") deal with the processes that follow attention:

1. Apparent brightness and color can be influenced by adjacent brightness and color.
2. Magnitude of stimulus and magnitude of perceived effect are related, but not in simple linear form (see Weber's and Fechner's psychophysical laws of perception).

3. Certain stimulus features (contours, straight lines) are accentuated in perception, while others (uniform areas) are not.
4. Gestalt qualities (such as good figure) will be preferentially perceived.
5. Objects and pictures of objects are remembered better than their names, and concrete words are remembered better than abstract words.

These principles, which are well handled by Fleming, coincide with the kind of informal advice which is often given to teacher trainees and fledgling designers. For example, the maxim "Go from the concrete to the abstract, from the simple to the complex, and from the familiar to the unfamiliar" is a homely old recipe which is remarkably useful.

In his fourth chapter ("Objects, Pictures and Words"), Fleming runs into two further difficulties. The first concerns modalities, that is, the strengths and weaknesses of sight and hearing. Fleming's exact words are: "Vision is a sense that is superb for representing spatial distinctions but relatively poor for temporal. Audition is a sense that is superb for representing temporal distinctions but relatively poor for spatial." (p. 22.) Part of this generalization seems true: It is difficult to represent spatial knowledge in sound (probably no practical designer would try to do so). On the other hand, the passage of time can be shown quite well (as sequence, order, succession) in texts and on film and television. For example, displays of social data (tables and Isotype charts) often show temporal trends; graphs are plotted with time as the independent variable; processes are shown stage by stage. Continuous movement is obviously well handled on film or television, and speech can be represented as printed words. An audio message does have some special qualities; for example, it can "pace" the learner, it can represent some things superbly well (e.g., spoken language and music), and audio tapes are cheap and simple to change. Apparently, Fleming's account of sense modality is too general and too symmetrical.

The second difficulty is caused by the decision to split signs into two classes, *digital* (words and numbers) and *iconic* (all pictures and diagrams). This distinction goes back to Morris (1938, 1946, 1964) and has been adopted by many audiovisual researchers, including Gibson (1954) and Knowlton (1966); see also Bruner (1966). Here are the original definitions from Morris (1938):

> A characterizing sign characterizes that which it can denote. Such a sign may do this by exhibiting in itself the properties an object must have to be denoted by it, and in this case the characterizing sign is called an *icon*; if this is not so, the characterizing sign may be called a *symbol*. A photograph, a star chart, a model, a chemical diagram are icons, while the word "photograph," the names of the stars and of the chemical elements are symbols (p. 24).

The definition contains two noteworthy presuppositions, one inside the other. First, it assumes that the primary source of knowledge and therefore

of communication is a world full of objects. This view of the world is pure logical atomism; Wittgenstein's *Tractatus* (1922) includes these dictums:

2.021 Objects make up the substance of the world.
2.12 A picture is a model of reality.
2.131 In a picture the elements of the picture are the representatives of objects.

Later in his life Wittgenstein came to believe that his *Tractatus* was profoundly wrong in building upon "primary elements" (i.e., objects). This change of mind, incidentally, caused him to reclassify diagrams as language games (Wittgenstein, 1953).

This dramatic shift of opinion by a great philosopher cannot be taken lightly; at the least it shows we should not accept Morris's definitions at face value. Suppose we recast the definition of iconic to bring it closer to its use in ordinary language, as follows: "An icon is an image or portrait of an object or person." This makes good sense but does not cover diagrams, indeed it does not cover any abstract graphic formats. Now it becomes clear that most of the graphic formats listed by Morris and Fleming are not iconic in this sense: not chemical diagrams (a chemical element is certainly not an "object" in any straightforward sense), not geometric figures, and perhaps not even maps (this is the second presupposition). Too much is included under Fleming's *iconic*, and his advice on digital versus iconic messages should be used warily.

Fleming's fifth chapter ("Perceptual Capacity") raises the same issues as did Travers's review discussed above. Chapters 6 and 7 deal with the perception of sets, time, space, and motion. Some key principles are:

1. Similar objects or objects placed close together will be perceived as related.
2. Familiar objects exhibit perceptual constancy.
3. Common themes, patterns, and structures assist the process of interpretation.
4. The spatial arrangement of a picture or diagram affects the process of interpretation.
5. Words in support of graphics can aid learning.
6. Perception of depth is influenced by relative size of familiar objects, perspective, texture, superimposition, and various qualities of light.
7. Perceptions of size, motion, and time duration may be aided by providing appropriate frames of reference or comparisons.

These are expansions of the basic themes in the first chapter.

The final chapter ("Perception and Cognition") is rather thin by present-day standards; for example, the crucial works by de Groot and Simon, though published before 1970, were not consulted by Fleming. Fleming's use of standard textbooks as his original sources led to a sound account of the traditional

research in perception but one which missed out on the modern rebirth of cognitive psychology (see Lindsay & Norman, 1972; Newell & Simon, 1972, and Pylyshyn, 1973). Overall this is a review of impressive scope and sound common sense. Its major conclusions (as listed above in shortened form) could help designers to improve their work, providing the pitfalls mentioned are given due attention. However, since the conclusions are rather too generalized for direct practical application (again the need for when/when not research), perhaps a skilled intermediary is needed to link practitioner and researcher. This link is the "transformer" (Macdonald-Ross & Waller, 1976), or instructional technologist.

This discussion of perception research has so far looked at the possibility of universal prescriptions derived from research. The three sources chosen (Abercrombie, Travers, and Fleming) give a fair idea of what perception research has to offer. There are, however, other worthwhile sources which may be consulted. Gibson (1954) offered a theory of pictorial perception based mainly on the realism dimension. This has been an influential paper, though it suffers from the same weakness as Morris's theory of signs. A diagram as a surrogate for reality is Gibson's idea; contrast that with a diagram as a way of representing problems, or with diagrams as language games. Another important paper is Gerbner's (1956) general model of communication, based on the Shannon-Weaver model of communication, which, as discussed above, has its limitations.

Gropper (1963) looks at graphic communication through the spectacles of behaviorism: "The general aim of instruction is to increase what was an initially low probability of occurrence to a high probability of occurrence. When this happens, responses are said to be under the control of stimuli" (p. 76). For graphics which have a strong task orientation, this may be a useful conception. Knowlton (1966) gives an interesting discussion of the definition of *picture*, though once again Morris's unsatisfactory theory of signs has a corrosive effect.

Particular Prescriptions

Category 1*b* includes particular prescriptions based on the results of research into limited problems. Most of the empirical evidence for the later sections of this review comes from this kind of limited research, and examples will be given in the appropriate places.

General Research Methods

Research methods are categorized as general and special purpose in categories 2*a* and 2*b*. We shall briefly consider three approaches to general research methods:

The physicalist model. Laboratory experiments with simplified stimulus material and close control of variables.

The pragmatic model. Field experiments with realistic stimulus material (ergonomics–human factors).

Theory-driven research. An example is the artificial intelligence–problem-solving model.

None of these models is exclusive, and a broad research program might use them all. In practice, however, researchers do tend to specialize in one of the three.

The physicalist model has often been used, but its relevance to graphic communication is problematic. The model uses simplified stimulus material and attempts to control each variable in standard laboratory conditions. Though copied from the physical sciences, this model lacks any strong theoretical components. Hypotheses are tested, but it is often unclear how they were selected in the first place. The experiments by Tinker (1963) into typography are regarded as classic examples of this approach; they will be discussed later in this review.

The pragmatic model used in human factors research has been quite successful and offers a plausible alternative to the physicalist approach. The pragmatic model also avoids any deep commitment to theory, but it conducts tests in realistic situations with stimulus material of full complexity. Of necessity this means that only the chief variables can be controlled. Coherent alternatives can be tested, with the aim of achieving large improvements that are robust under field conditions. Statistically significant improvements may not be sufficient, and, contrariwise, results of no significant differences may mask differences which are significant in the real world (see Johnson & Klare, 1961). (This is also one of the key problems with the physicalist model.) Important sources for the pragmatic approach are Baker and Grether (1954), Chapanis (1959, 1966; Chapanis, Garner, & Morgan, 1949), and Bartlett and Mackworth (1950). Most of this work has been done on the ergonomics of radar displays, aircraft cockpits, instrument panels, and road signs. Therefore it is the research methods rather than the results that are most useful in this setting.

The invasion of cognitive psychology by ideas drawn from artificial intelligence is certainly one of the most important developments in modern psychology. Its significance for a theory of graphic communication is as follows. One of the key steps in solving a problem is to represent it "so as to make the solution transparent" (Simon, 1969); in other words, to fit the task onto the strategies available for its solution. This means that *a graphic format is a canonical representation for problems of a certain class;* the format allows people to manage certain tasks that would be impossible or difficult if posed in words alone. Such a theory makes sense of the majority of graphic formats:

all mathematical diagrams are clearly designed to facilitate problem solving (see Hogben, 1960; Polya, 1945; Wertheimer, 1945); so are most scientific diagrams (see discussion in Toulmin, 1953), as well as tables, nomograms, algorithms, and most of the other devices reviewed in this chapter. Even the diagrams in anatomy textbooks could be considered as problem-solving tools for dissection and surgery. The work of Kennedy (1974) on picture perception is quite interesting, but might have been improved if Kennedy had made connection with current work on pattern recognition and scene analysis (for which see Minsky & Papert, 1969, 1972; Winston, 1970). The key sources for the "graphic device as problem representation" are Bobrow and Collins (1975), de Groot (1965), Kleinmutz (1966), Newell and Simon (1972) and Simon (1969). Interesting precursors to this idea can be found in the work of the Gestalt school (Koffka, 1935; Wertheimer, 1945).

Special-Purpose Research Methods

The field of research into perception is remarkable for the variety of instruments and methods available to the researcher. Some of these (for example eye-movement recorders, tachistoscopes) can be used on a fairly wide range of problems; others (such as the Ishikawa color test) are used for one purpose only. These instruments tend to condition the way researchers look at problems, and usually for the better, for the effect is to suggest ways of translating research questions into action.

To summarize: the field of perception research can offer both *results* and *experimental methods* for use by graphic communicators. The review by Fleming (1970) was selected for detailed analysis, and a shortened version of his principles was given. Two models of research which I believe are worth special attention are:

The artificial intelligence–problem-solving model, whereby a graphic device is seen as a canonical form for representing certain kinds of problems.

The human factors–ergonomics model for conducting realistic experiments on applied problems.

PRESENTING QUANTITATIVE DATA

If it can't be counted, it isn't science.
Lord Kelvin (attrib.)
All social facts are statistical.
Otto Neurath

The two quotations that head this section illustrate the great importance of quantitative data in our scientific-industrial age. As a matter of fact, both

statements are rather contentious; such extreme positivism is rare in present-day philosophers of science. Nevertheless, adequate collection, organization, and presentation of numerical data are essential in our world. In this review there is no space to deal with the collection and analysis of data, though it must be said that a good communicator needs to understand the conceptual foundations of the graphic devices he uses. To design a chart or table the designer may need to go back to source documents to check the definition of key terms, the sampling procedures, and so on. This does require some basic familiarity with research methods, and it may be that the training of graphic designers could be improved in this respect.

There are two major reviews of the graphic presentation of quantitative data (Funkhouser, 1937, and Macdonald-Ross, 1977). Wright's broad survey (1977) also includes a discussion of quantitative data. Funkhouser's historical survey is a splendid piece of scholarship which describes the origin and development of all the graphic formats which are used for presenting data. This survey shows how a graphic format is invented to meet some need that existing formats could not satisfy, how the original idea is improved (in an erratic, piecemeal manner), and finally how it is standardized.

Tables

Until recently the design of tables for presenting statistics has been an arcane art, understood well by few people. Now, work by Ehrenberg (1977) has clarified the process by showing how application of a few simple principles can markedly improve the design of tables:

1. Round numbers to two significant digits. This facilitates mental arithmetic.
2. Provide row and/or column averages. They are reference points.
3. Figures are easier to compare in columns; so use columns for the most important comparisons.
4. Order rows and columns by size of numbers and not, for example, by alphabetical order of the labels.
5. Columns and rows should be set compactly, not artificially spaced out to fit the page. Space can be used to distinguish relevant blocks of figures.

Ehrenberg's rules are supported by examples (one of which is shown here in Figure 1), by some informal trials and formal tests, and by detailed discussion of the objections his fellow scientists have raised in discussion. For example, if two-digit rounding is criticized for "losing data," Ehrenberg points out that much precision is spurious, and, furthermore, errors of rounding are usually trivial in effect. Moreover, the rule has a distinct benefit for the user: We can see, manipulate, and communicate data more easily in this

TABLE A

Table from "Facts in Focus" (London: Penguin, 1974). As published, it breaks most of Ehrenberg's rules.

Unemployment in Great Britain

	1966	1968	1970	1973
Total unemployed (thousands)	330.9	549.4	582.2	597.9
Males	259.6	460.7	495.3	499.4
Females	71.3	88.8	86.9	98.5

Source: *Facts in Focus*

TABLE B

The same data as Table A, but with rows and columns interchanged and numbers rounded and placed in decreasing order of size. Visual comparisons and mental arithmetic are now straightforward. The effects of such rearrangements are even more marked with complex tables.

Unemployment in Great Britain

GB	Unemployed (000's)		
	Total	Male	Female
1973 (D)	600	500	99
'70 (B)	580	500	87
'68 (A)	550	460	89
'66 (C)	330	260	71
Average	520	430	86

TABLE C

The same data arranged to show the deleterious effect of artificial spacing-out to fit the page.

Unemployment in Great Britain

	Unemployed		
	Total	Male	Female
1973	600	500	99
'70	580	500	87
'68	550	460	89
'66	330	260	71

Figure 1. Examples of Ehrenberg's rules applied to a simple table.

simplified form. The rule is also consistent with the limitations of short-term memory: "If any task, however simple, is interposed between [the subject] hearing the items and his repeating them, the number he can retain drops to two" (Simon, 1969, pp. 39–40). According to Ehrenberg, the reading of a table is a self-interrupting task, which fits Simon's description quite closely.

The main benefit of tabular presentation is its compactness; a great deal of data can be put on a single page. Also, even with the two-digit restriction a table presents numbers more exactly than bar or pie charts do. Therefore it seems likely that tables will remain the preferred format for professional users. The great weakness of tables is their abstract nature. A table consists entirely of abstract symbols—words and numbers. For example, 333 and 999 occupy the same space, and it takes an act of cognition to make sense of them. When hundreds of numbers are arrayed in a complex table most people find it difficult to sort out the significant features; indeed, there are many who cannot interpret even the simplest tables. No doubt it would help if such skills were taught in schools, but they are not, and the practising communicator has to take people as they are. Therefore it is common practice to use charts for a general readership. Bar charts show quantity by length, and Isotype charts show quantity by rows of standard symbols. In effect this reduces the need for abstract cognition and offers the data as a series of visual comparisons (this/that, here/there, now/then).

Charts and Graphs

The relative effectiveness of bar charts, circle charts, pie charts, and graphs has been a subject of some controversy. Experimental studies have gradually sorted out the main issues, though several researchers made the mistake of using poor-quality stimulus material and inappropriate tasks. A detailed review of this work has recently been completed (Macdonald-Ross, 1977). The main conclusions are:

1. The quantity and the logical and visual arrangement of data have an important effect on learning (Washburne, 1927).
2. No form is more effective in all respects than all other forms (Washburne, 1927).
3. Bar charts are generally superior to circle charts (Croxton & Stein, 1932) and to line graphs (Culbertson & Powers, 1959).
4. Circles (or squares) of differing sizes should be avoided; if used they should be range-graded (in stepped sizes) and a key provided to show the number represented by each step (Meihoefer, 1969, 1973).
5. Where possible, labels should be placed directly on bars or lines; they should not be indirectly keyed (Culbertson & Powers, 1959).

6. For general use, horizontal bar charts were understood better than tables, and tables were understood better than text (Feliciano, Powers, & Kearl, 1963).
7. Use text to support charts and tables (Washburne, 1927; Feliciano et al., 1963).
8. If pie charts are used, avoid fine angular discrimination (E. Hoch, personal communication).
9. In general, the advice given by expert designers has been vindicated by subsequent empirical tests (Macdonald-Ross, 1977).
10. Any graphic format can be executed well, or poorly, for a particular purpose. This is often a more significant variable than the choice of format (Macdonald-Ross, 1977).

The Isotype Chart. An important graphic format for general readers is the pictorial chart, in particular the Isotype system developed by Otto Neurath

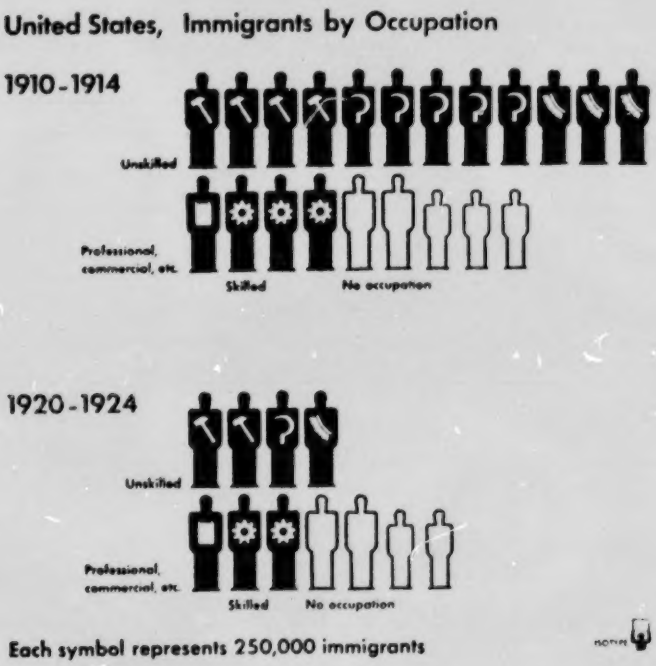


Figure 2. A typical isotype chart.

(1936). The Isotype system is especially adapted for presenting social statistics to the general public and is the main alternative to bar charts for this purpose (see Figure 2). The main principles of the Isotype system are:

1. The subject matter is represented by standard iconic signs.
2. Each sign stands for a given quantity or percent.
3. To show larger quantities, use more signs (*not* larger signs).
4. Arrange the signs to make a "visual argument."

The last principle needs some clarification, for it introduces a new term, *visual argument,* to which Neurath attached a great deal of weight. Neurath assumed that communication was for a purpose: The statistics were not just displayed, they were organized to get a message across. In the Isotype system, the graphic communicator is called a "transformer" to express his role as an intermediary between the source and the reader. Since the transformer is in a position of control he must be, according to Neurath, an educated person of impeccable integrity. Neurath said, "The transformer is the trustee of the public"—a splendid way to express the relationship.

The heart of a visual argument is an explicit comparison or a series of comparisons, for example:

Imports and exports
of corn and steel
into and out of the U.S.A. and the U.S.S.R.
in 1910, 1930, 1950, and 1970.

This kind of data would provide the basis for an Isotype chart, many hundreds of which were produced during the lifetime of the Isotype Institute. The use of visual comparisons is fully consistent with Fleming's (1970) first principle, discussed above. Neurath wrote only one formal account of his system (O. Neurath, 1936), so to see the full scope one has to look at the product. The social atlas (O. Neurath, 1930) and the social history (O. Neurath, 1939) are beautiful sources, worth many hours of study. Other accounts worth consulting are Marie Neurath's history of the Isotype Institute (M. Neurath, 1974), and the books by Koberstein (1973) and Modley (1937).

In the early days of the Isotype Institute charts were informally tested on groups of schoolchildren, but these trials were never reported in journals. This lack of documentation is quite normal with formative evaluation, but it does lay the practitioner open to the charge that the graphic methods used are just "a matter of opinion," and from time to time a skeptical researcher puts the question to an empirical test. A case in point is the series of experiments on pictorial charts, bar charts, graphs, and tables by M. D.

Vernon (1946, 1950, 1953, 1962). A fair summary of Vernon's conclusions would be: Differences in format make little or no difference to the performance of subjects; especially, "No all-round advantage is gained by using pictorial charts."

If Vernon's conclusion could be sustained graphic communication would have received a severe blow, for what is the point of graphic ideas like Isotype if they cannot be read with greater facility than tables or graphs? A good deal of expertise is needed to produce charts, and they are therefore relatively costly. However, there is no reason to accept Vernon's no-difference results at face value. Her experimental design contains some serious flaws, and her graphic devices were incompetently designed. A test of a table that has been fairly well set in type against a poor graph or a dreadful pictorial chart is invalid; no general conclusions can be drawn. For reasons of this kind the inferences Vernon drew from her results were not justified (see discussion in Macdonald-Ross, 1977).

Nomograms. Nomograms are graphic devices for representing equations on a plane surface. They are widely used in engineering design and to a lesser extent in the social and physical sciences. Nomograms can be divided into two classes, or distinct graphic formats:

Abac. Equation drawn as a graph on Cartesian or logarithmic coordinates.

Alignment chart. Three or more scales arranged so that a straight line joining two known values cuts the third scale to give the required value.

These two formats are logically identical but psychologically quite different, as Figures 3 and 4 show. As mentioned earlier, a basic tenet of the general theory of problem solving is that the way a problem is represented can affect the ease and manner of its solution. This is a case in point, for there is widespread testimony from expert users that alignment charts are much easier to use than abacs. Engineers have often conducted comparative tests for their immediate practical purposes, though few of these tests have found their way into the literature of education or psychology. Basic references are Allcock and Jones (1932), Douglass (1970), D'Ocagne (1899), Ford (1969) and Griffin (1932). Beeby and Taylor (1973) is a recent example of the systematic formative testing of an abac; unfortunately, they did not try out the alignment chart format on this occasion. D'Ocagne is the inventor of the alignment chart, one of the most recent additions to the range of graphic alternatives and one of the most important.

Since the chief purpose of the nomogram is to make exact data available for operational use, its chief competitor is the table. Operational tables may break Ehrenberg's two-digit rule, since they are not used to detect general trends but to provide exact data for some operational purpose. The choice

Graph for Estimating Reliability

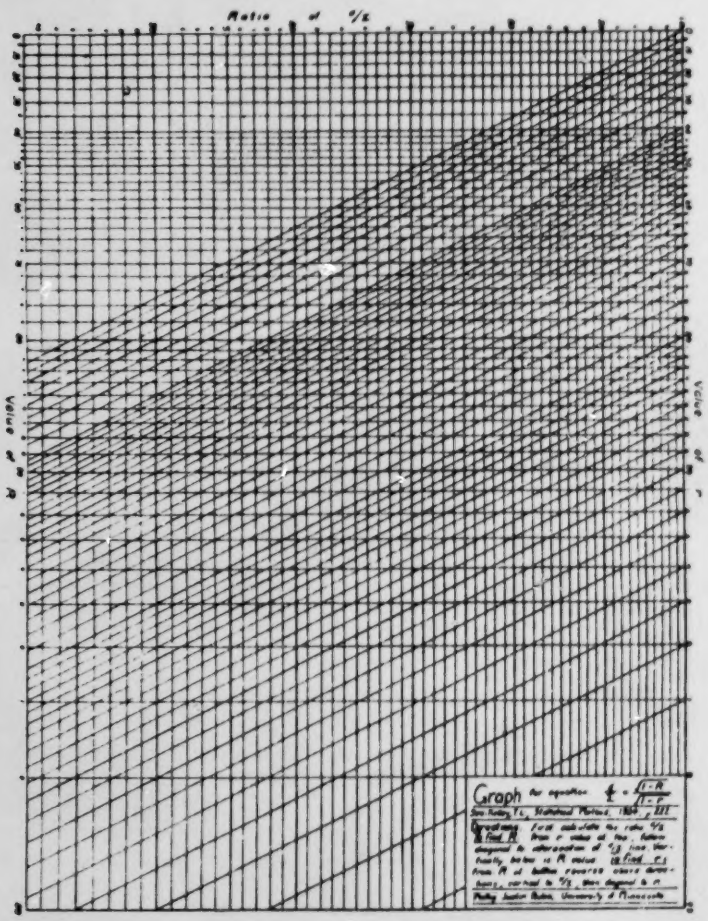


Figure 3. An abac for estimating reliability. (From P. J. Rulon, "A Graph for Estimating Reliability in One Range Knowing It in Another," *Journal of Educational Psychology*, 1930, *21*, 140–142.)

between nomogram and table involves a complex tradeoff among cost, space, convenience, accuracy, and speed. These tradeoff situations provide one good reason why no one graphic format is suitable for all purposes. Of course, there can be good methods (satisficing solutions) for particular cases.

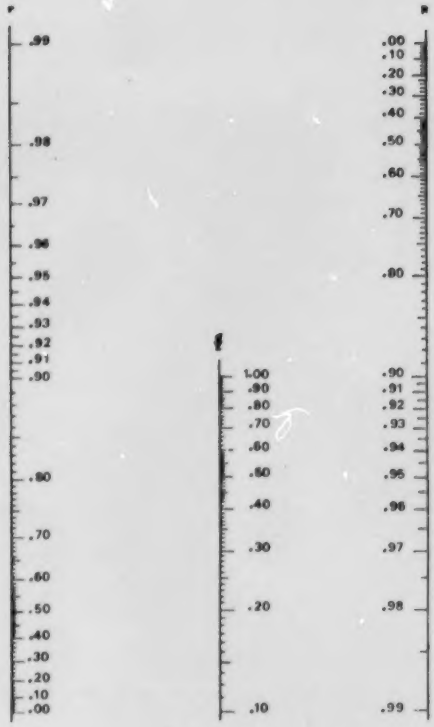


Figure 4. An alignment chart for estimating reliability based on the same formula as Figure 3. From E. E. Cureton and J. W. Dunlap, "A Nomograph for Estimating the Reliability of a Test in One Range of Talent When Its Reliability Is Known in Another Range," *Journal of Educational Psychology*, 1929, *20*, 537–538.

Advice for Graphic Designers

For practical graphic designers the following advice is the best that can be offered at present:

1. For showing general trends and relationships to:
   a. The general public, use *horizontal bar charts* or *Isotype* charts. Bar charts are easier to construct, but Isotype charts are more likely to attract and motivate the reader. Avoid change for the sake of change.
   b. The professional, use *tables*, and follow Ehrenberg's guidelines.

2. For presenting exact data:
   a. To show the results of experiments or investigations, use *graphs* (on Cartesian or logarithmic scales) or *tables.*
   b. To present exact data for operational purposes, use *nomograms* (especially alignment charts) and *tables* (the two-digit rule does not apply to these tables).

Other graphic devices may be used, but variation for its own sake is not advisable. These systems of representation are partly or wholly symbolic, embodying codes that must be learned by the user. Switches in the format therefore entail switches in the user's interpretive procedures, thus increasing the risk of misinterpretation. The advice Neurath gave on this score was "Everything in a chart should have a meaning; and nothing should be changed without a reason." This also applies to charts in series.

Another caveat: It is not always possible to see whether the users should be classified as *general public* or *professional.* Indeed, these terms were deliberately chosen for their broad denotations. For example, high school students and beginning university students may be regarded as untrained for this purpose and treated as members of the general public; graduate students, however, should be treated as professionals. Categories 1*b*, 2*a*, and 2*b* above are mainly for the trained professional user, but again this guideline must be used with common sense. A high school student may be able to handle simple graphs and tables with just a short training session, and teachers should be encouraged to regard graphic interpretation as a basic reading skill.

The use of Cartesian and other graphs for displaying experimental data is ubiquitous in science and technology, so it is included under 2*a*. This practice has not been researched extensively by applied psychologists but has developed over many years by a process of gradual, piecemeal evolution. Therefore, there is a prima facie case for assuming that graphs do display such data fairly effectively, and in any event the practice is so deeply entrenched that it will last. At the start of this review, two sources of knowledge were listed: formal tests and expert practitioners. Ideally, these sources coincide and reinforce each other, but sometimes one must make do with whatever knowledge is available.

SCIENTIFIC AND TECHNICAL DIAGRAMS

Scientific discourse consists of ordinary language, technical terms, diagrams, equations, and special notations; this is the apparatus used by scientists to describe their subject matter. A study of how these linguistic and graphic systems work together would be important and interesting and would certainly

help us understand the central issues of graphic communication. No such enterprise has yet been attempted, and even partial studies covering particular subject matters or particular types of diagrams are quite rare.

There *has* been continuing interest in the kind of technical diagrams used for maintaining, operating, and troubleshooting complex equipment, however. This section therefore discusses two types of diagrams:

Scientific diagrams used to help explain and illustrate.

Technical or operational diagrams which help the user to carry out tasks.

The section *omits* the types of diagrams discussed elsewhere, such as the graphs and nomograms described in the preceding section.

One consequence of using a simple iconic-symbolic distinction to classify graphic formats (as discussed above) is that too many kinds of diagrams are lumped together as "iconic," including many that are in no way images of objects. As an alternative, I suggest a simple list of *purposes* which could be used to develop a more sophisticated classification:

Iconic purpose. Here the purpose is to show what an object looks like, and to identify and label key parts.

Data display purpose. Here the purpose is to display the results of empirical observations.

Explanatory purpose. Here the purpose is to show the logical relationships between key ideas.

Operational purpose. Here the purpose is to help the reader to perform some well-specified task.

Some diagrams have a single purpose, but others combine two or more. For example, mathematical diagrams can be both explanatory and operational; biological diagrams can be both iconic and explanatory; engineering drawings can be both iconic and operational. These purposes are achieved by the use of rules or codes which, in effect, specify how the diagrams shall be constructed and interpreted. Sometimes these rules are explicit and are taught formally to students (e.g., graphs in physics), and sometimes the rules remain tacit and not articulated, in which case they are picked up in an informal fashion (e.g., medical illustrations). This raises the possibility that diagrams could be separated into families according to the kinds of interpretive rules they embody. Such a classification would make it much easier to design valid experiments to test their effectiveness.

Although in general scientists are not aware of the role diagrams play in their work, there are some notable exceptions. Allweis (1971) is a magnificent survey of the role played by systems diagrams in physiology; Hogben's (1960) history of mathematics pays full attention to the development of mathe-

matical notations and diagrams,' and both Meredith (1961) and Toulmin (1953) have some important ideas to contribute:

> One of the factors which makes graphic organisation so powerful is that it can draw simultaneously on a number of different codes and so achieve great economy of expression . . . . some codes are more obvious than others. Some are so little obvious as to be invisible (Meredith, 1961, p. 149).

> In geometric optics one learns to draw inferences, not in verbal terms, but by drawing *lines* . . . . this [kind of] diagram plays a logically indispensible part in the physicist's explanation.
>
> The heart of all major discoveries in the physical sciences is the discovery of novel methods of representation, and so of fresh techniques by which inferences can be drawn—and drawn in ways which fit the phenomena under investigation (Toulmin, 1953).

Toulmin's second, rather daring, thesis can be understood if "methods of representation" is interpreted in a suitably broad way to include mathematical systems as well as graphic devices. Some well-known examples would be the use of calculus in Newtonian dynamics, the role played by Riemannian geometry in the general theory of relativity, and the role played by chemical equations and the periodic table in 19th-century chemistry.

Experimental studies on scientific diagrams are few and far between (see the survey by Holliday, 1973). Dwyer (1972) has conducted a series of experiments on diagrams of the human heart, but unfortunately this work is weakened by poor-quality stimulus material and by a terminal test of uncertain validity. These illustrations were originally part of a linear programmed text written by Dwyer for the purpose of testing some of the principles of programmed learning. Dwyer adopted Gibson's "realism continuum" (a direct descendant of Morris's sign theory). This outlook emphasizes one aspect of biological diagrams (representing form and labeling parts) and undervalues other aspects (providing visual explanations and providing aids to operational action). The terminal test therefore consists of rote recall and low-level comprehension items—though learning names is just one aspect of biology. Even if Dwyer's test items are accepted at face value, the diagrams he used are (to put it mildly) not up to the best standards of biological illustration. Perhaps, as one reasonable idea, the quality of a graphic device is more important than the choice of format, providing the task items are within the domain of the alternative formats. If so, Dwyer's results cannot be generalized.

Experiments on technical or operational diagrams have been rather more successful, largely because the rules for constructing the diagrams and the criteria for their effectiveness are so much clearer. Also, their military and industrial importance has attracted more research interest.

Systems diagrams are good examples; they are used as job aids to help workers set up, operate, maintain, and repair complex equipment. The content and purpose of the diagrams are decided by task analysis, and the typical end product has less "nice-to-know" information and less prose and uses diagrams to carry the burden of the job-relevant instruction. Typical tasks are:

Assembling a machine-gun.
Repairing a television set.
Repairing a tank in the field.
Troubleshooting electronic equipment at sea.

Examples of diagram formats used in job-support documentation are:

Photographs or drawings of equipment.
Functional block diagrams of the system.
Maintenance dependency charts.
Algorithms.

For further details of this specialized but important work, consult Baker (1958), Glaser (1962), Shriver (1960), Shriver and Fink (1964), and Ware, Miller, and Constantinides (1968, 1969). One general caution is in order: these systems depend on task and systems analysis, which is a highly skilled activity. The U.S. Armed Forces were fortunate to have the services of some outstanding researchers in their institutes during and after World War II. Other organizations have since copied the *form* of the graphics without achieving the quality of *analysis* that made the graphic aids effective. Organizations that use job-support documentation should realize that the documentation rests absolutely on the quality of prior analysis; it is no use expecting a technical document department to produce effective material if it is not supported by top-class analysts.

Another, older type of operational diagram is the engineering drawing. The history of engineering drawing is told by Booker (1963), and the rediscovery of Leonardo da Vinci's Madrid codex (Reti, 1974) should also be noted. This is one of the few areas of graphic communication which has a standardised training and examination system. This formalization has good and bad consequences: it makes for widespread usability and standardization (which is absolutely essential in the mechanical engineering industry), but it also helps to perpetuate outmoded and dysfunctional conventions. Researchers can play a useful role as change agents in questioning and testing established practice. Some recent experiments on the effectiveness of different projections

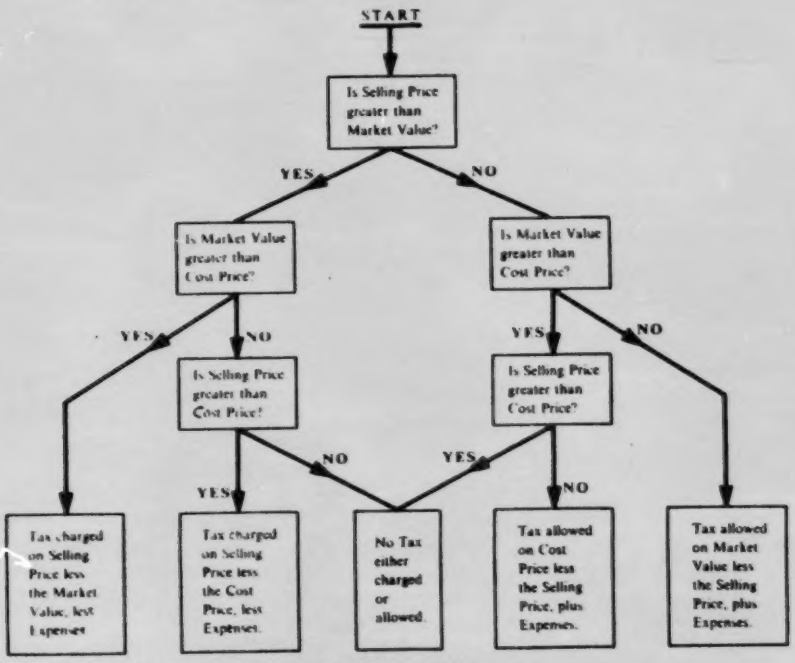
and labels are perhaps a start to this process of critical improvement (Spencer, 1973; Cheney & Spencer, 1974).

ALGORITHMS

> An algorithm is a visual instrument of telling.
> *Lewis*

The term *algorithm* is used in two different but related senses: the ordinary language (OL) algorithm, and the computer algorithm. OL algorithms show rules, regulations, procedures, and instructions in noncontinuous prose—usually as flowcharts, sometimes in list format (see Figure 5). The source is

Flow chart for Capital Gains Tax


START
Is Selling Price greater than Market Value?
YES
NO
Is Market Value greater than Cost Price?
Is Market Value greater than Cost Price?
YES
NO
YES
NO
Is Selling Price greater than Cost Price?
Is Selling Price greater than Cost Price?
NO
YES
YES
NO
Tax charged on Selling Price less the Market Value, less Expenses
Tax charged on Selling Price less the Cost Price, less Expenses.
No Tax either charged or allowed.
Tax allowed on Cost Price less the Selling Price, plus Expenses.
Tax allowed on Market Value less the Selling Price, plus Expenses.

Note 'Market value' is based on the quoted value at April 1965.

Figure 5. An ordinary language algorithm. (From B. N. Lewis, I. S. Horabin, and C. P. Gane, *Flow Chart, Logical Trees, and Algorithms for Rules and Regulations* [London: HMSO, CAS Occasioned Papers No. 2, 1967].)

usually a rule or regulation in prose linked by the words *if, then, unless.* This leads to complex nested subclauses that are extremely difficult—often impossible—to retain and sort out in the mind. The object of an OL algorithm is to break up this prose into its constituent parts and arrange it on the page so that the reader has to deal with only one thing at a time. If the reader is asked one question at a time in simple, active voice, the language can be understood by a much larger target population. Lewis and Wason are the co-originators of OL algorithms, and their papers are well worth reading (Jones & Wason, 1965; Lewis 1970; Lewis & Cook, 1969; Lewis, Horabin, & Gane, 1967; Wason, 1968; Wason & Johnson-Laird, 1972).

In mathematics and computer science an algorithm is a procedure which produces correct results (in contrast with a *heuristic*). This is a usage which deserves to be kept distinct from OL algorithms. Markov (1961) and Trakhenbrot (1963) spell out the foundational theory, and Gerlach, Reiser, and Brecke (1975) and Merrill (1974) are two good recent reviews of the use of algorithms in teaching and learning. For most teachers algorithms mean simply flowcharts, and since the format does lend itself to classroom activities maybe the next generation will get some practice in their construction and use.

CARTOGRAPHY

Maps are ancient graphic devices. One clay map from Mesopotamia is dated at 2,500 B.C.; and the cartography of the Graeco-Roman civilization was remarkably sophisticated. The needs of navigators and explorers from the European nations led to the accurate maps we now know, and as the scientific-industrial revolution gathered pace cartographers developed special-purpose (thematic) maps to display particular kinds of social and economic data. According to Thrower (1972), "all the common techniques of thematic cartography in use today had been developed by 1865."

Recently there has been a growing awareness that a map succeeds only if the information it contains can be extracted and used by the reader. This has led to empirical studies of map design, such as those by Bartz (1970), Christner and Ray (1961), Cuff (1973), Ekman, Lindman, & Olsson (1961), Hopkin (1973), Meihoefer (1969, 1973). This concern for the reader is typical of our times and is mainly due to the growth of instructional technology during and after World War II. The standard of these empirical studies in cartography is quite admirable, perhaps because the experiments were designed by researchers who were familiar with the subtleties of the stimulus material. Cartography is one discipline where graphic communicators can occupy regular university posts.

NOTATIONS

> The concept of position puts our arithmetic in the front rank of useful inventions. *Laplace*

Notations and codes are invented because of the limitations of ordinary language: notations to say things that can hardly be expressed in ordinary language, and codes to hide messages that would otherwise be all too clear. Notations are certainly important for the growth and expression of ideas and hence are of interest to us. But few philosophers have paid them much attention. Leibniz (c. 1966) has some interesting ideas (see Ishiguro, 1972, and Tymieniecka, 1964), and Frege (1879) and Goodman (1969) are two important essays on notations by modern philosophers.

Mathematical and logical notations are of great importance, the standard sources being Cajori (1928), Neugebauer (1951), and Smith (1958). Formal experiments on the effectiveness of notations are almost never done; mathematics proceeds by trial and experience of new notations, as happens with the evolution of diagrams. There are dozens—perhaps hundreds—of other kinds of notations which have never been classified and analysed, though they must play an indispensable role in thought and communication.

COMIC STRIPS

Comic strips are in their element when used to show the irony of life, the vagaries of human nature, and the complexities of personal interaction. The work of Schultz (1952) and Feiffer (1958) provides perfect examples; in their hands a comic strip has eye-opening qualities. But what are we to make of comic strips used to "add interest" to subjects like golf, investment, and military tasks? On the one hand readers may find the format attractive, and that can help motivate them to read further. On the other hand, there is the distinct possibility that the illustrations may not help the reader understand the substance of the message. There have been some informal trials, and one recent handbook for editors of army manuals (Kern, Sticht, Welty, & Hauke, 1975) does include comic strips as a device for graphic communication. Green and Courtis (1966) give an interesting discussion of the relevance of Shannon's information theory to the perception of cartoon figures.

TYPOGRAPHY

> *Die Typographie ist ein Instrument der Mitteilung.* *Moholy-Nagy*

Typography is the art of arranging print on the page. The new technology of printing has freed the typographer from most of the mechanical limitations

imposed by hot metal; now any marks on paper can be reproduced. This freedom marks a permanent change in the typographer's art. Once he was a skilled interpreter of mechanical constraints; now he can become a communicator—that is the sense of Moholy-Nagy's manifesto for the new typography.

Surely the arrangement of type is a cut-and-dried issue which was sorted out centuries ago? Surely type cannot affect the quality of educational materials? These are natural reactions of many untrained people, for it takes a trained eye to spot the troubles caused by poor typography. The untrained reader may realize that some books tend to be "easygoing" and others do not, but he is not equipped to diagnose the source of any difficulties. Since the causes of reading difficulty may lie in the subject matter, the author's prose style, the typography, or the reader's skill or prior knowledge (or any combination thereof), the business of diagnosis is indeed complex.

The first kind of typographic problem is the maintenance of basic standards. The setting of continuous prose has long been mastered, but violations of well-founded principles abound. Recently in a small survey I found:

Ragged *left* edge. This disrupts the eye-movement routine.

Illegible second color. Yellow or orange can hardly be seen under household lights.

Lack of contrast between print and paper; print too grey; background screen too dark.

6-point type size in book setting.

Uneven and excessive word spacing (very common).

Large slabs of text set in uppercase and italic.

Often in paperback editions three or four suboptimal conditions occur together. This is quite serious for the reader; as Tinker (1963) showed, these suboptimal features have a cumulative effect. Such mistakes are not theoretically interesting, but they are important to the reader. Commonsense, training, and quality control should dispose of all such cases; but the fact is that errors of this type do occur quite often in educational books.

Educational materials also introduce problems for the typographer, for the only task which has been truly mastered by the craft of typography is the setting of continuous prose. Diagrams and photographs, captions, in-text questions and answers, instructions, and formulas all break up the text and provide novel problems for the typographer. Moreover, many educational texts are designed by people who have no training at all in typography. They do not know which problems are new and which are not, and this reduces their chance of success almost to zero. Several surveys look at the special typographic problems of educational material (Hartley & Burnhill, 1976, 1977; Hartley, Fraser, & Burnhill, 1973; Macdonald-Ross & Waller, 1975b; Watts & Nisbet, 1974). There is no sign that these problems can be

solved easily, though they are now being dissected and sorted out for the first time.

There has been a great deal of research on the basic elements of text setting. Tinker's famous summary (1963) is still indispensable, but there is some doubt as to whether the problems he investigated were well formulated. If we take this research at face value (as Rehe, 1974, does), then we are bound to conclude that a great deal of useful work has been done, and what we need is more of the same. If, however, we take a more skeptical look at the experimental design, then maybe (as Macdonald-Ross & Waller, 1975a, suggest) some of the effort put into empirical testing has been wasted. Is it appropriate to do single-variable tests on simplified stimulus material? How does such stimulus material relate to the real design problems of the typographer? The trouble is that most of the variables do interact strongly; for example, justified setting, line length, and word spacing cannot be treated as independent, for they are not. It is worth reading Fisher's (1935) account of the single-factor experiment:

> In expositions of the scientific use of experimentation it is frequent to find an excessive stress laid on the importance of varying the essential conditions *one at a time* . . . . in the state of knowledge or ignorance in which genuine research, intended to advance knowledge, has to be carried on, this simple formula is not very helpful. We are usually ignorant which, out of innumerable possible factors, may prove ultimately to be the most important, though we may have strong presuppositions that some few of them are particularly worthy of study (p. xxx).

Despite this clear-cut warning in an important methodological text, most typographical research has used single-variable design (see Tinker, 1963). This makes the results difficult to use in real typographic situations, though there is some broad consensus on such variables as type size, print and paper contrast, and the illegibility of upper-case text.

Tinker's work on the cumulative effect of suboptimal arrangements and his ideas about the "hygenic reading situation" are both relevant and practical. Imagine a text full of conceptual muddle, unclear expression, visual confusion, and suboptimal setting being read by someone who is tired and disinterested, sitting in poor light, with the text not at right angles to the line of sight, and in a noisy room full of interruptions and distractions. This gives you some idea of a real-life reading situation (we might get fewer no-difference results in conditions like these). Suboptimal settings may not produce large effects when tested one by one in clinically perfect reading conditions, but they do produce most significant effects when several occur together and the text is read under poor conditions.

The special problems of newspaper typography are described by Arnold (1969), Evans (1973), Frayman, Griffiths, and Chippindale (1975), Hutt (1967,

1973), and Sellers (1968). Though meant for trainee journalists, these books contain many ideas which could be used by instructional technologists. Some key issues (such as allowing the reader to make the choices that suit him) are well solved by newspapers and magazines. Also worth noting are Chaundy (1970) and Swanson (1971) on the typography of mathematics, and Wright (1975), Wright and Barnard (1975), and Civil Service (1972) on the design of forms.

The design of letterforms is still a live issue. With the introduction of cold composition, calligraphy is now a practical notion, and the creation of suitable typefaces for non-Roman languages is very important indeed. It is extraordinary that Chinese, Japanese, and Arabic still do not have really satisfactory character sets, though (at last) work is going on to meet these needs. It seems that the mainland Chinese government has decided to shelve the alphabetic notion and simplify the basic 5,000 characters instead. This is a sensible decision, since the many dialects of Chinese (some of which are virtually distinct languages) prevent any simple phonetic basis for their language. The mechanical problems of composition will be much simplified by electronic setting, so the chief argument against the idiographic character has less force now.

Typography is a specialized skill, and instructional technologists working with text materials should develop their understanding of it before embarking on experimental work. Good places to start are Dowding (1966), Gill (1931), Morison (1946), Spencer (1952), Tschichold (1967), Williamson (1956), and Twyman (1970).

CONCLUSION

The practitioner who designs a graphic device is acting, as we all do, with imperfect knowledge. A graphic device is an artifact, intended to get across a particular idea to some particular readers. There is no way a science of instruction could lay down minutely detailed prescriptions for all conceivable situations. This is simple realism. However, it is possible to put together the knowledge we already have, to improve it, and to make it more easily available. Reliable knowledge applied intelligently will improve the effectiveness of graphic communication. That is what this review has tried to do.

The knowledge we have about the use of graphic devices is derived from two sources: the expert practitioner and the formal scientific experiment. These are two quite separate traditions, and yet it is necessary to bring them together for their mutual benefit. First of all, let it be said that there are master performers: they are not a fiction of my imagination. Their expertise is real enough, for they can repeatedly produce effective solutions to problems that defeat less skilled practitioners. The knowledge of a master practitioner is mainly tacit (i.e., not articulated). It is the product of practice, experience,

and careful thought, but usually the master does not explain his methods. Even where a master has put his thoughts onto paper, they provide only a sketchy outline, insufficient for the purpose of instruction and experimental testing.

By displaying publicly the rationale of the master performer, certain crucial benefits can be obtained. The knowledge can be examined, criticized, tested, and improved. And the knowledge can be communicated to others; younger designers can be trained; minimum standards can be set and maintained. These are absolutely vital benefits which can be gained only by the intervention of researchers willing to open themselves to the possibility of learning some of the basic elements of the master's craft. It does not seem possible to design fruitful experiments in graphic communication if the researcher is entirely ignorant of the object of his research, or, worst of all, if he is not just ignorant but ignorant of his ignorance. There is no doubt that master performers can be improved upon. I do not imagine that their way is better than the way of experiment, but externalizing this knowledge can be a great step toward genuine scientific understanding and reliable prescriptions for the designer.

The experimental work must not be taken for granted. It is a proven way to deepen our understanding, but it is not easy to do experimental work which will stand up to rigorous cross-examination. As many readers will know, it is not possible to lay down hard-and-fast rules for how scientific work shall be conducted—at any rate, all such attempts have failed so far. But it *is* possible to notice occasions when researchers have taken a wrong turn. These mistakes are interesting, and we can learn from them. Moreover, it is absolutely essential for mistaken results and erroneous techniques to be weeded out, else neither researchers nor practitioners can know whether they build on solid ground or on quicksand. I am well aware that I have trained a fairly skeptical eye on the research literature, not because I lack faith in the scientific method (far from it), but because I believe that skepticism is a necessary and useful part of the scientific method. I have been just as demanding in my behind-the-scene search for master practitioners, though this cannot be demonstrated in a written paper.

Despite this skeptical outlook, there turns out to be a surprising stock of knowledge available, and this chapter lists some of the most important sources. I believe that the gulf between researcher and graphic designer ought to be bridged, and that bridge should most likely be embodied in a skilled professional communicator. Such a role-player does exist in other media—for example, a television producer acts as the key coordinator of all the contributing specialties. There is no equivalent role in text production, though there should be. Sometimes instructional technologists do play this role, but more often the coordinating function is just omitted. Consequently a good deal of substandard textual material is used for education and instruction.

If we can build up our knowledge and our personal expertise, and if we can apply this expertise in the right way, then it will be possible to raise the effectiveness of texts.

REFERENCES

Abercrombie, M. L. J. *The anatomy of judgement: An investigation into the processes of perception and reasoning.* London: Hutchinson, 1960.

Allcock, H. J., & Jones, J. R. *The nomogram: The theory and practical construction of computation charts.* London: Pitman, 1932.

Allweis, C. Control systems in physiology, biology and medicine. *Israel Journal of Medical Sciences,* 1971, *7* (Supplement).

Arnold, E. C. *Modern newspaper design.* New York: Harper, 1969.

Baker, C. A., & Grether, W. A. *Visual presentation of information* (Tech. Rep. 54-160). Wright Air Development Center, 1954.

Baker, R. A. *The determination of job requirements for tank crew members* (Tech. Rep. 47). Alexandria, Va., 1958.

Bartlett, R. C., & Mackworth, N. H. *Planned seeing: Some psychological experiments.* HMSO Air Ministry Air Publications 3139B. London, 1950.

Bartz, B. S. An analysis of the typographical legibility literature: Assessment of its applicability to cartography. *Cartographic Journal,* 1970, *7,* 10-16.

Beardsley, A. *The birth, life and acts of King Arthur embellished with designs by Aubrey Beardsley.* London: Dent, 1893.

Beeby, A. W., & Taylor, H. P. J. How well can we use graphs? *Communicator of Scientific and Technical Information,* 1973, *17,* 7-11.

Bland, D. *A history of book illustration: The illuminated manuscript and the printed book.* London: Faber, 1958.

Bobrow, D. G., & Collins, A. (Eds.). *Representation and understanding.* New York: Academic Press, 1975.

Booker, P. J. *A history of engineering drawing.* London: Chatto & Windus, 1963.

Bruner, J. S. *Toward a theory of instruction.* Cambridge, Mass.: Belknap Press, 1966.

Cajori, F. *A history of mathematical notations.* LaSalle, Ill.: Open Court, 1928.

Chapanis, A. *Research techniques in human engineering.* Baltimore: Johns Hopkins Press, 1959.

Chapanis, A. *Man-machine engineering.* London: Tavistock, 1966.

Chapanis, A., Garner, W. R., & Morgan, C. T. *Applied experimental psychology: Human factors in engineering design.* New York: Wiley, 1949.

Chaundy, T. W. *Printing for mathematics: Aids for authors and rules for compositors and readers at the University Press, Oxford.* London: Oxford University Press, 1970.

Cheney, R. L., & Spencer, J. Dimensional information on engineering drawing. *Ergonomics,* 1974, *17,* 343-363.

Christner, C. A., & Ray, H. W. An evaluation of the effect of selected combinations of target and background coding on map-reading performance. *Human Factors,* 1961, *3,* 131–146.

Civil Service, Management Services Division. *Design of forms in government departments.* London: HMSO, 1972.

Croxton, F. E., & Stein, H. Graphic comparison by bars, squares, circles and cubes. *Journal of American Statistical Association,* 1932, *27,* 54-60.

Cuff, D. J. Colour on temperature maps. *Cartographic Journal*, 1973, *10*, 17-21.
Culbertson, H. M., & Powers, R. D. A study of graph comprehension difficulties. *Audio Visual Communication Review*, 1959, *7*, 97-100.
DeGroot, A. *Thought and choice in chess*. Gravenhage, Netherlands: Mouton, 1965.
DeGroot, A. Perception and memory versus thinking. In B. Kleinmutz (Ed.), *Problem solving*. New York: Wiley, 1966.
D'Ocagne, M. *Traite de nomographie*. Paris: Gauthier-Villars, 1899.
Douglass, R. D. Nomograph. *Encyclopedia of science and technology*. New York: McGraw-Hill, 1970.
Dowding, G. *Finer points in the spacing and arrangement of type*. London: Wace, 1966.
Dwyer, F. M. *A guide for improving visualized instruction*. State College, Pa.: State College Learning Services, 1972.
Ehrenberg, A. S. C. Rudiments of numeracy. *Journal of Royal Statistical Society* (Series A, vol. 40), in press.
Ekman, G., Lindman, R., & William, O. W. A psychological study of cartographic symbols. *Perceptual and Motor Skills*, 1961, *13*, 355-368.
Evans, H. *Editing and design: A five-volume manual of English, typography and layout*. London: Heinemann, 1973.
Feiffer, J. *Sick, sick, sick*. New York: McGraw-Hill, 1958.
Feliciano, G. D., Powers, R. D., & Kearl, B. E. The presentation of statistical information. *Audio Visual Communication Review*, 1963, *11*, 32-39.
Fisher, R. A. *The design of experiments*. Edinburgh: Oliver & Boyd, 1935.
Fleming, M. L. *Perceptual principles for the design of instructional materials* (ED-03 7093). Indiana University: Bloomington AV Center, 1970.
Ford, L. R. Nomography. *Encyclopaedia Britannica*, Chicago, 1969.
Frayman, H., Griffiths, D., & Chippindale, C. *Into print: A guide to publishing non-commercial newspapers and magazines*. London: English Universities Press, 1975.
Frege, G. *Conceptual notation and related articles*. London: Oxford University Press, 1879.
Funkhouser, H. G. Historical development of the graphical representation of statistical data. *Osiris*, 1937, *3*, 269-404.
Gerbner, G. Toward a general model of communication. *Audio Visual Communication Review*, 1956, *4*, 171-199.
Gerlach, V. S., Reiser, R. A., & Brecke, F. H. *Algorithms in learning, teaching and instructional design* (Tech. Rep. 51201). Tempe: Arizona State University, Educational Technology, 1975.
Gibson, J. J. A theory of pictorial perception. *Audio Visual Communication Review*, 1954, *2*, 3-23.
Gill, E. *An essay on typography*. London: Sheed & Ward, 1931.
Glaser, R. *Training research and education*. Pittsburgh: University of Pittsburgh Press, 1962.
Gombrich, E. H. The visual image. *Scientific American*, 1972, *227*, 82-96.
Goodman, N. *Languages of art: An approach to a theory of symbols*. London: Oxford University Press, 1969.
Green, R. T., & Courtis, M. C. Information theory and figure perception: The metaphor that failed. *Acta Psychologica*, 1966, *25*, 12-36.
Griffin, H. D. How to construct a nomogram. *Journal of Educational Psychology*, 1932, *23*, 561-577.
Gropper, G. L. Why is a picture worth a thousand words? *Audio Visual Communication Review*, 1963, *11*, 75-95.

Hartley, J., & Burnhill, P. *Textbook design: A practical guide.* Paris: Unesco Division of Materials and Techniques, 1976.

Hartley, J., & Burnhill, P. Fifty guidelines for improving instructional text. *Programmed Learning and Educational Technology,* 1977, *14,* 65-73.

Hartley, J., Fraser, S., & Burnhill, P. A selected bibliography of typographical research relevant to the production of instrumental materials. *Audio Visual Communication Review,* 1973, *22,* 181-190.

Hogben, L. T. *From cave painting to comic strip: A kaleidoscope of human communication.* London: Parrish, 1949.

Hogben, L. T. *Mathematics in the making.* London: Macdonald, 1960.

Holliday, W. G. Critical analysis of pictorial research related to science education. *Science Education,* 1973, *57,* 201-204.

Hopkin, V. D. Human factors in the design of maps. In *Visual presentation of technical data.* Ergonomics Research Society and the Society of Industrial Artists and Designers. Reading, England: University of Reading, Typography Unit, 1973.

Hutt, A. *Newspaper design.* London: Oxford University Press, 1967.

Hutt, A. *The changing newspaper: Typographic trends in Britain and America 1622-1972.* London: Gordon Fraser Gallery, 1973.

Ishiguro, H. *Leibniz's philosophy of logic and language.* London: Duckworth, 1972.

Johnson, F. C., & Klare, G. R. General models of communication research: A survey of the developments of a decade. *Journal of Communication,* 1961, *11,* 13-26, 45.

Jones, S., & Wason, P. C. *The logical tree project.* University College, London: Department of Psychology, 1965.

Kennedy, J. M. *A psychology of picture perception.* San Francisco: Jossey-Bass, 1974.

Kern, R. R., Sticht, T. G., Welty, D., & Hauke, R. N. *Guidebook for the development of army training literature.* Alexandria, Va.: Human Resources Research Organization, 1975.

Kleinmutz, B. (Ed.) *Problem solving: Research, method and theory.* New York: Wiley, 1966.

Knowlton, J. Q. On the definition of "picture." *Audio Visual Communication Review,* 1966, *14,* 158-183.

Koberstein, H. *Statistik in bildern.* Stuttgart: C. E. Poeschal, 1973.

Koffka, K. *Principles of Gestalt psychology.* London: Kegan Paul, 1935.

Lewis, B. N. *Decision logic tables for algorithm and logical trees.* London: HMSO, 1970.

Lewis, B. N., & Cook, J. A. Toward a theory of telling. *International Journal of Man-Machine Studies,* 1969, *1,* 129-176.

Lewis, B. N., Horabin, I. S., & Gane, C. P. *Flow charts, logical trees and algorithms for rules and regulations.* CAS Occasional Papers no. 2. London: HMSO, 1967.

Lindsay, P. H., & Norman, D. A. *Human information processing: An introduction to psychology* (2nd ed.). New York: Academic Press, 1977.

Macdonald-Ross, M. How numbers are shown: A review of research on the presentation of quantitative data in texts. *Audio Visual Communication Review,* in press.

Macdonald-Ross, M., & Smith, E. *Graphics in text: A bibliography.* Milton Keynes, England: Open University, Institute of Educational Technology, 1977.

Macdonald-Ross, M., & Waller, R. Criticisms, alternatives and tests: A conceptual framework for improving typography. *Programmed Learning and Educational Technology,* 1975, *12,* 75-83. (a)

Macdonald-Ross, M., & Waller, R. *Open University texts: Criticisms and alternatives.* Milton Keynes, England: Open University, Institute of Educational Technology, 1975 (b).

Macdonald-Ross, M., & Waller, R. The transformer. *Penrose Annual, 1976, 69,* 141-152.

Markov, A. A. *Theory of algorithms.* Washington: National Science Foundation, 1961.

Meihoefer, H. J. The utility of the circle as an effective cartographic symbol. *Canadian Cartographer,* 1969, *6,* 105-117.

Meihoefer, H. J. The visual perception of the circle in thematic maps: Experimental results. *Canadian Cartographer,* 1973, *10,* 63-84.

Meredith, P. *Learning, remembering and knowing.* London: English Universities Press, 1961.

Merrill, P. F. *Algorithmic organization in teaching and learning: The literature and research in the USA.* Tallahassee: Florida State University, Center for Educational Design, 1974.

Minsky, M. & Papert, S. *Perceptions.* Cambridge, Mass.: MIT Press, 1969.

Minsky, M., & Papert, S. *Progress report.* Cambridge, Mass.: Massachusetts Institute of Technology, Artificial Intelligence Laboratory, 1972.

Modley, R. *How to use pictorial statistics.* New York: Harper, 1937.

Morison, S. *First principles of typography.* London: Cambridge University Press, 1946.

Morris, C. W. *Foundations of the theory of signs.* Chicago: University of Chicago Press, 1938.

Morris, C. W. *Signs, language and behavior.* New York: Prentice-Hall, 1946.

Morris, C. W. *Signification and significance: A study of the relation of signs and values.* Cambridge, Mass.: MIT Press, 1964.

Neugebauer, O. *The exact sciences in antiquity.* Copenhagen: Munksgaard, 1951.

Neurath, M. Isotype. *Instructional Science,* 1974, *3,* 127-50.

Neurath, O. *Gesellschaft und wirtschaft.* Leipzig: Bibliographisches Institut, 1930.

Neurath, O. *International picture language.* London: Kegan Paul, 1936.

Neurath, O. *Modern man in the making.* New York: Knopf, 1939.

Newell, A., & Simon, H. A. *Human problem solving.* Englewood Cliffs, N.J.: Prentice-Hall, 1972.

Polya, G. *How to solve it: A new aspect of mathematical method.* Princeton, N.J.: Princeton University Press, 1945.

Pylyshyn, Z. W. What the mind's eye tells the mind's brain: A critique of mental imagery. *Psychological Bulletin,* 1973, *80,* 1-24.

Rackham, A. *Illustrations to Wagner's Ring of the Niebelung* (2 vols.). London: Heinemann, 1911.

Rehe, R. F. *Typography: How to make it most legible.* Indianapolis: Design Research Publications, 1974.

Reti, L. (Ed.). *The unknown Leonardo.* London: Hutchinson, 1974.

Schulz, C. *Peanuts.* New York: Holt, Rinehart, 1952.

Sellers, L. *The simple subs book.* Oxford: Pergamon, 1968.

Shannon, C. E., & Weaver, W. *The mathematical theory of communication.* Urbana, Ill.: University of Illinois Press, 1949.

Shriver, E. L. *Determining training requirements for electronic system maintenance.* (HumRRO Res. Rep. 63.) Alexandria, Va.: Human Resources Research Office, 1960.

Shriver, E. L., & Fink, C. D. *FORECAST systems analyses and training methods for electronic maintenance training* (HumRRO Res. R. 13). Alexandria, Va.: Human Resources Research Office, 1964.

Simon, H. A. *The sciences of the artificial.* Cambridge, Mass.: MIT Press, 1970.

Smith, D. E. *History of mathematics.* London: Constable, 1958.

Spencer, H. *Design in business printing.* London: Sylvan Press, 1952.

Spencer, J. Presentation of information on engineering drawings. In *Visual presentation of technical data.* Ergonomics Research Society and the Society of Industrial Artists and Designers. Reading, England: University of Reading, Typography Unit, 1973.

Swanson, E. *Mathematics into type.* Providence, R. I.: American Mathematical Society, 1971.

Thrower, N. J. W. *Maps and man: An examination of cartography in relation to culture and civilization.* Englewood Cliffs, N.J.: Prentice-Hall, 1972.

Tinker, M. A. *Legibility of print.* Ames: Iowa State University, 1963.

Toulmin, S. E. *The philosophy of science: An introduction.* London: Cambridge University Press, 1953.

Trakhenbrot, B. A. *Algorithms and automatic computing machines.* Boston: D. C. Heath, 1963.

Travers, R. M. W. *Man's information system: A primer for media specialists and educational technologists.* Scranton, Pa.: Chandler, 1970.

Tschichold, J. *Asymmetric typography.* New York: Reinhold, 1967.

Twyman, M. *Printing 1770-1970: An illustrated history of its development and uses in England.* London: Eyre & Spottiswood, 1970.

Tymieniecka, A. T. *Leibniz' cosmological synthesis.* Assen, Holland: Van Gorcum, 1964.

Vernon, M. D. Learning from graphical material. *British Journal of Psychology,* 1946, *36,* 145-58.

Vernon, M. D. The visual presentation of factual material. *British Journal of Educational Psychology,* 1950, *20,* 174-185.

Vernon, M. D. A further study of visual perception. London: Cambridge University Press, 1952.

Vernon, M. D. Presenting information in diagrams. *Audio Visual Communication Review,* 1953, *1,* 147-158.

Vernon, M. D. *The psychology of perception.* Baltimore: Penguin, 1962.

Ware, J. R., Miller, E. E., & Constantinides, J. L. *Pictorial methods of instruction for the M73 machine gun and the caliber .45 automatic pistol.* (HumRRO Cons. Rep.) Alexandria, Va.: Human Resources Research Office, 1968.

Ware, J. R., Miller, E. E., & Constantinides, J. L. *Project PIMO (Presentation of Information for Maintenance and Operation).* (TR 69-155). Washington: Serendipity Inc., 1969.

Washburne, J. N. An experimental study of various graphic, tabular and textual methods of presenting quantitative material. *Journal of Educational Psychology,* 1927, *18,* 361-376, 465-476.

Wason, P. C. The drafting of rules. *New Law Journal,* 1968, *118,* 548-549.

Wason, P. C., & Johnson-Laird, P. N. *Psychology of reasoning: Structure and content.* London: Batsford, 1972.

Watts, L., & Nisbet, J. *Legibility in children's books: A review of research.* Windsor, Berks., England: National Foundation for Educational Research, 1974.

Wertheimer, M. *Productive thinking.* New York: Harper, 1945.

Williamson, H. A. F. *Methods of book design: The practice of an industrial craft.* London: Oxford University Press, 1956.

Winston, P. H. *Learning structural descriptions from examples.* (Project Mac, MAC TR-76). Cambridge, Mass.: Massachusetts Institute of Technology, 1970.

Wittgenstein, L. *Tractatus logico-philosophicus.* London: Routledge & Kegan Paul, Ltd., 1922.

Wittgenstein, L. *Philosophical investigations.* Oxford: Blackwell, 1953.

Wright, P. Forms of complaint. *New Behaviour*, 1975, *1*, 206-209.
Wright, P. Presenting technical information: A survey of research findings. *Instructional Science*, 1977, *6*, 93-134.
Wright, P., & Barnard, P. 'Just fill in this form': A review for designers. *Applied Ergonomics*, 1975, *6*, 213-220.

How Numbers Are Shown

A Review of Research on the Presentation of Quantitative Data in Texts

MICHAEL MACDONALD-ROSS

INTRODUCTION

It seems that civilised man has always needed to record trade, property, scientific knowledge, and social information as quantitative data. Systems of numbering are one of the earliest inventions—as old as written language, so far as one can tell. There were numbering systems in the Egypt and Sumeria of 3,500 B.C., and we can hazard a guess that the complexity of a civilised society does always require an efficient way to record numerical data. Our own numbering system, the Hindu/Arabic decimal system, embodies the concept of position, which is, as Laplace says, a "profound and important idea, which puts our arithmetic in the first rank of useful inventions".

In the last 150 years the collection and use of quantitative data has blossomed again, due to the industrial/scientific revolution. Now, every discipline in the social, biological, and physical sciences, all applied science and every instrument of social and governmental policy depend upon the appropriate use of quantitative data. By the middle of the last century a great variety of graphic formats had been invented for the

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presentation of such data: graphs, tables, bar charts, pie charts, cartograms—these devices were all in use a century ago. More recently there have been attempts to identify the strengths and weaknesses of these various formats by analysis and example and by formal tests. This review is an attempt to pull this scattered information together and identify the key findings, the main issues, and the unresolved problems.

Ideally, we should start by considering the many ways people use quantitative data to explain and control the world they live in. This would make a fascinating intellectual history; but it would be such a major work of scholarship as would take the best part of a lifetime to complete. Therefore, the present review does not deal directly with the collection and analysis of data. We are here examining the way such data are *presented in texts* to the world at large. Readers interested in the history of mathematics can get leads from Cajori (1928, 1894, 1928), Dantzig (1939), Hogben (1949, 1960), Midonick (1968), Smith (1958), Smith and Ginsburg (1937), and Smith and Karpinski (1911). Readers interested in the collection and analysis of social data should consult Coombs (1964), Ehrenberg (1975), Torgerson (1958), Tukey (1976), and Zeisel (1947). There are also many works dealing with the problems of data manipulation in physics, biology, engineering, and other special disciplines; and of course, progress in the fundamentals of statistical theory is directly or indirectly connected with data manipulation. This brief list gives some idea of the task that would confront anyone who tried to give a completely satisfactory account of the collection and manipulation of quantitative data.

Anyone who wishes to present quantitative data goes through three stages: Which data to present? Which format to choose? How to execute that particular format competently? This review concentrates on the two latter stages, that is, on the *presentation* of the data. All three stages are unified by the author's *purpose*: the reason why the research was done or, more simply, by what the writer wants to get over to the reader. There is no such thing as "facts displayed" pure and simple. All facts presented in papers and textbooks are selected from a huge pool of possibilities. Sometimes facts are selected intelligently, appropriate for a purpose; sometimes not—but always they are selected. However, an author is not free to say whatever he or she pleases: one is constrained by

the data one is working with, and by the likely impact of the message on the reader. Having a purpose enables the writer to select between those alternatives which are legitimate and workable.

Can empirical research help us improve the way we present quantitative data? This review examines all the relevant empirical studies this author has been able to find; and this may be the first time such an extensive review of this field has been conducted. Every paper has been looked at according to a severe criterion, namely: can practical communicators rely upon the results? For an experiment to meet such a demand it should be directed towards a relevant question, valid in design and execution, properly reported, and robust when applied in the field. Many experiments fail one or more of these tests and so cannot be wholly relied upon in practice. Where any experiments have been rejected the reasons are spelled out carefully—if experimental procedure is to advance we must avoid making the same mistakes over and over. Experiments take time and cost money; if a researcher goes astray it may be many years before anyone else gets round to examining the same questions. This accept/reject formula might be rather stultifying if it were not supplemented by constructive ideas and hints culled both from experiments and practical communicators. After all, even a poor study may contain some good ideas, and many questions of moment to the practical communicator have never been put to any formal test.

This review therefore makes use of the accumulated experience of competent practical communicators, that is, the scientists, engineers, and designers who spend much of their lives in the practical art of presenting data. There is plenty of evidence that, on occasion, such practitioners can see more truly and deeply than their experimental colleagues (see, for example, the discussion on pictorial charts). This ought not to surprise us unduly, for it has often been said that scientific knowledge grows out of a deep understanding the investigator has for the subject under investigation (see for instance Lorenz, 1971; Polanyi, 1958, 1967). Practitioners conduct many informal tests which are never reported, but which nevertheless help them to improve their judgement—indeed, in curriculum development, such informal tests are honoured with a special label: "formative evaluation". At any rate, this reviewer will not be so bigoted as to suppose that

only formal laboratory experiments reported in the psychological journals can count as "knowledge". In a recent review of the research on typography a conceptual framework was presented whereby the tacit knowledge of designers could be harnessed to the practice of empirical testing (Macdonald-Ross & Waller, 1975b)

Nevertheless, this is a review of empirical research, not a "how to do it" manual. For practical communication to be effective it is necessary for empirical research to be studied, but that is not sufficient by itself. Many subtle tricks of the expert designer have never been studied, especially the art of adjusting the various parts of a design so that one coherent whole is produced. A great deal of experience, intuition, critical skill, and trial of alternative solutions goes towards the design of good communication: this *artful* process will never be replaced by formal laboratory investigations.

This review tries to identify those research conclusions which can be relied upon, and those research procedures which have proved especially fruitful or defective. The "arithmetical summation" method of reviewing is rejected by this reviewer. The critical method adopted here shows that research conclusions cannot be taken at face value and hence should not be summated.

The creation of a conceptual framework for this review has been exceptionally difficult. It is generally accepted that quantitative data can be presented in various *formats*, each format (though allowing variation) unified by its particular code or set of rules for construction and interpretation. So, one possible framework would be to take formats one by one, detailing all the appropriate experiments. But that would have split some work into a dozen fragments and require impossibly detailed cross-referencing. Another approach is to take authors one by one chronologically. Since each worker has his or her style this would put emphasis on the methodology. On the other hand not all workers address the same issues. In this review the first division is made by task criteria or purpose of the communication, the second division by format, and then by authors chronologically:

- ☐ presenting general trends and comparisons
  - a. abstract formats (graphs, tables, bar and circle charts, maps)
  - b. pictorial charts
- ☐ presenting exact numbers (tables, nomograms, maps)

This classification does have its defects: for example, there are certain graphs and certain maps that can be used either for educational purposes (as "visual arguments", to use Neurath's phrase) or for operational purposes (as sources of exact data for action). On the other hand, the scheme draws attention to one of the most frequent and crucial experimental mistakes—asking subjects to perform tasks inappropriate to the format or purpose of the communication.

Those results which upon analysis seem valid and robust are listed after each individual author in abbreviated form. The reviewer recognises that, for all the care that has indeed been taken, others might have summarised the research with different emphases.

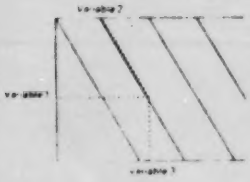
The reader will find many sources which give information and advice on presenting quantitative data. One indispensable source is the splendid historical survey by Funkhouser (1937). The textbooks by Brinton (1916), Karsten (1923), and Modley (1937) were once landmarks, though they are now out of print. Of the many hundreds of books on practical statistics Zeisel (1947) and Ehrenberg (1975) are worth special mention. Presenting quantitative data in maps is dealt with by Monkhouse and Wilkinson (1971) and Robinson and Sale (1969). There has been no previous detailed analysis of the research covered by this review though readers might like to look at Wright (1977), Macdonald-Ross and Smith (1977), and Macdonald-Ross (1977).

DEFINITIONS AND EXAMPLES

This section contains the definitions of key terms used in this review and examples of the chief alternative formats in which quantitative data may be presented. The list does not include all the possible variations and hybrids, but does provide a basic vocabulary. Please note especially the restricted sense in which the term *graph* is used here. Statistical terms are used as in Kendall and Buckland (1975).

These terms may not be entirely clear to readers who meet them for the first time, so they have been supplemented by schematic diagrams and by brief comments about their purposes, strengths, and weaknesses. Some formats have such a range of uses that no simple summary does them real justice; and all formats are heavily dependent on the practical skill of the designer. A diagram which in one person's hands is a visual disaster might be transformed into excellence in the hands of another. This prevents any simple algorithmic approach to the choice of format.

FIGURE 1
Abac



Abacs

Nomograms drawn on coordinate grids are *abacs*. They are easier to construct than alignment charts but less easy to use. (See Figure 1.)

Alignment Charts

Alignment charts consist of a system of nomograms in which variables are represented as a series of scales. In general, all nomograms other than abacs are alignment charts. Easier to use than abacs, they are less easy to construct. (See Figure 2.)

FIGURE 2
Alignment Chart

Bar Chart (Bar Graph)

The term *bar chart* has a broader usage than "histogram", though the graphic form—bars of constant width and variable length—is similar. Bar charts may show more than one dependent variable and may be horizontal, vertical, or segmented. The segmented bar chart loses the advantage of a fixed baseline for visual comparison, but saves space. Figure 3 shows the three forms of the bar chart.

FIGURE 3
Bar Charts

(a) Vertical Bar Chart *(b) Horizontal Bar Chart* *(c) Segmented Bar Chart*

Cartesian Grid

If the axes of a coordinate grid bear arithmetic scales, the grid is a Cartesian grid.

FIGURE 4
Chloropleth

Cartogram

A map displaying quantitative data is a cartogram. Seldom general-purpose, cartograms are usually single-purpose or "thematic". Chloropleths, isopleths, and dot maps are typical cartograms.

Chloropleth

A chloropleth is a cartogram having areas of equal value represented by the same colour or shade or texture. Figure 4 shows an example.

FIGURE 5
Circle Chart

Circle Charts

Circle charts use the size of circles to represent quantity. They have been strongly criticized on the grounds that the eye does not make comparisons of area with any facility or exactness. (See Figure 5.)

Coordinate Grid

FIGURE 6
Coordinate Grid

Most usually graphs are drawn on coordinate grids. Such a grid is based on two rectilinear bisecting straight lines: the horizontal axis is called the abscissa or x-axis; the vertical axis is called the ordinate or y-axis. The point of intersection of the two axes is known as the origin, and the position of any other point in the plane can be denoted by a pair of coordinates. For most purposes one uses only that part of the grid where both variables are positive, hence the usual L-shaped graph axes. Maps representing small areas may be drawn on coordinate grids. (See Figure 6.)

Curve

The lines drawn on grids are called curves (even straight lines). There are statistical procedures which help researchers decide which curve best fits the given data. A curve may be represented by an equation; likewise any equation phrased in terms of x and y may be graphed. For example, the graph of $y = ax + b$ is always a straight line. Curves fall into families, each described by one such equation and each with a characteristic shape. Some of the most common are shown in Figures 7, 8, 9, and 10.

FIGURE 7
Straight-Line Graph

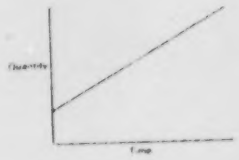


FIGURE 8
Normal Curve

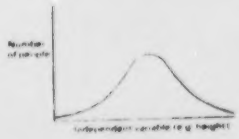


FIGURE 9
Exponential Curve

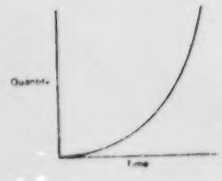


FIGURE 10
Ogive or Cumulative Frequency Curve

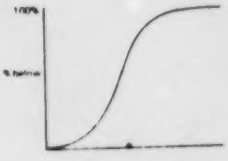


FIGURE 11
Multiple-Line Graph

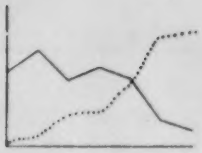
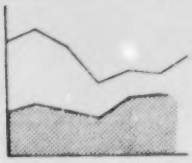


FIGURE 12
Segmented Graph



The meanings of such families or types of distribution are familiar to the working scientist and are spelt out in standard textbooks on statistics. Such graphs may occur as histograms if the data are grouped and will be shaped differently if non-Cartesian grids are used. Clearly, subjects will vary greatly in the prior knowledge they bring to the task of interpreting and using such graphs.

Two variations of the graph format are worth noting: the multiple-line graph and the segmented graph. The multiple-line graph allows easy comparison between two or more graphs drawn to the same coordinates; the segmented graph uses one line as the base for the next line. The segmented graph is generally thought to be unsatisfactory, for it embodies several obvious sources of confusion for the reader. (See Figures 11 and 12.)

Data

Data are the agreed facts, got by observation, survey, or experiment and reported in a source document. Data may be individual (a value for each item) or grouped (items collected into classes), continuous or discrete (values limited, e.g., to whole numbers). The data may be presented directly (as measured or counted) or derived (e.g., as percentages).

FIGURE 13
Dot Map

Dot Map

Individual items or grouped data may be represented as dots on a cartogram to form a dot map. Figure 13 shows an example.

Frequency Polygon

The frequency polygon is, essentially, a histogram masquerading as a graph. The data are grouped, the midpoints of the data plotted and joined. You cannot read off intermediate points on a frequency polygon, though the form of the curve suggests (misleadingly) that you can. Generally regarded as an inferior format, the polygon has been used to avoid superimposing histograms. (See Figure 14.)

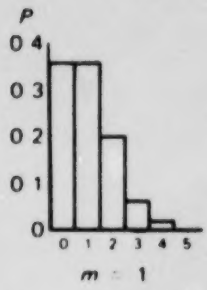
FIGURE 14
Frequency Polygon

Graph

A graph is a line drawn on a coordinate grid to show the relationship between two variables. The term "graph" therefore includes both the grid and the line and maybe the necessary labels for the axes as well. Unless otherwise specified the grid is Cartesian. Some experimenters have used the term graph to cover Cartesian graphs, pie charts, bar graphs, and pictorial charts. In this review the term will never be so used; these alternative formats each have their own principles of

construction and so deserve separate labels. The confusion is caused by the similarity between "graph", which has a specific meaning, and "graphic", an adjective which can be used to refer to all nonprose ways of presenting information.

FIGURE 15
Histogram

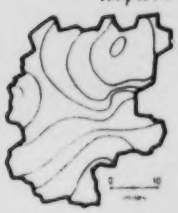


Histogram

The histogram is visually similar to the bar chart since data are grouped and quantity is shown by length of columns. Histograms have three special conditions: the figures must cover one set of data, the class intervals must be equal, and there must be a numerical scale on both axes. In general, any curve can be turned into a histogram by grouping data. Therefore, the shape of histograms can also be described by equations. Figure 15 shows a typical Poisson distribution.

Isopleth

FIGURE 16
Isopleth



An isopleth is a cartogram having lines that join points of the same quantity or value (for example, contour maps). Figure 16 shows an example.

Flow Map

A flow map is used to show flows (e.g., by the number or width and direction of lines). Figure 17 shows an example.

Map

FIGURE 17
Flow Map

Maps are two-dimensional representations of selected aspects of the earth's surface. Maps are sometimes divided into "general-purpose" maps open to a variety of uses (for example, an atlas) and special-purpose or "thematic" maps which present data of a specialised kind. This dichotomy cuts across the educational/operational classification used in this review. All maps discussed in this review are cartograms.

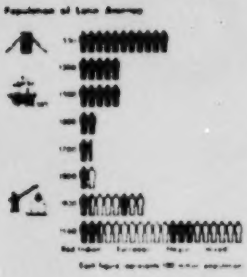
Nomogram

A nomogram is a "computation chart" representing formulae or empirical data. Their object is to allow the working scientist or engineer to obtain values directly (e.g., by laying a ruler across scales or graphs) instead of working from equations. Thus, each nomogram is defined by a clear set of operational tasks that the user may perform. Nomograms are divided into abacs and alignment charts.

Pictorial Charts (Ideogram, Pictogram, Pictograph)

Pictorial charts use iconic symbols in place of numbers; in this way the subject matter of the chart is directly associated with the quantity. Thus, they are less abstract than bar or pie charts, and much less abstract than tables of numbers. Two types are found: those in which greater quantity is represented by larger symbols ("bad system" according to

FIGURE 18
Isotype Pictorial Chart



Neurath) and those in which greater quantity is shown by repeating symbols of the same size. The best-known method is Neurath's Isotype where each symbol stands for a specified number or percentage. Despite their deceptively simple appearance pictorial charts require great skill to design. They are recommended for less numerate readers and for special visual impact. (See Figure 18.)

Pie Charts

Pie charts are circle graphs subdivided into segments. They take up less space than bar charts, but the eye does not make fine distinctions between angles with any ease. (See Figure 19.)

FIGURE 19
Pie Chart

Prose

Ordinary language in written or printed form is prose; it may contain numerical data. Graphic forms (such as maps, diagrams, tables, graphs, charts, etc.) are sometimes collectively described as "alternatives to prose", but prose can be a pretty useful alternative or supplement to a graphic device ("twice as many . . .").

Quantitative Data

Quantitative data are numerical data, such as measurements or counts.

Statistic

A statistic is a summary value calculated from a sample of observations. Statistics usually summarise the characteristics of a distribution such as the normal curve; these are statistics of central tendency (e.g., mean, mode, median), dispersion (e.g., standard deviation), and relative position in a distribution (e.g., quartile, decile).

Symbol

A symbol is a sign with special meaning, that is, a sign plus its connotation. Here it usually means an iconic (pictorial) symbol used in place of words or numbers on a chart. For example, lines or bars may be labelled with symbols, and symbols are the basic building blocks of pictorial charts.

Table

Source data are often presented as a table. Tables show numbers in the form of a matrix, that is, a rectilinear array of horizontal and vertical rows. They are not recommended for communicating data to the general public; tables are most useful for fellow professionals. Both constructing and reading tables require skill of a high order.

Value(s)
Individual item(s) which together constitute the data. A value is always a value of a variable.

Variable
A variable is any quantity (actually, any theoretical construct) which can take any one of a specified set of values. The dependent variable is the one counted for chosen values of the independent variable. Thus we may estimate population (dependent) alive at particular times (independent). Usually the independent variable is plotted on the x-axis and the dependent variable on the y-axis (see Cartesian grid). Variables may be continuous, noncontinuous, binary, scaled (see standard statistical textbooks).

PART I: PRESENTING GENERAL ASPECTS OF DATA

This part reviews research into methods used to present general aspects of data. This includes especially the display of trends and comparisons for education or general information for the lay reader. The presentation of exact numbers is here of secondary importance; instead, the reader is meant to grasp the meaning or significance of the data in some particular context. Usually the reader will be expected to make comparisons and appreciate *patterns* of data but not necessarily to perform exact calculations.

Abstract Formats

Tables, graphs, bar charts, circle graphs, pie charts, and—to some extent—maps are more abstract than the pictorial charts dealt with in the next section. These abstract formats look the same no matter what the content: you must read verbal labels (legends) to understand the message. Naturally, this abstractness tends to be a barrier between the message and the reader. It follows that much of the designer's art goes to making the information more immediate (for example, by adding pictorial symbols to line graphs) and to reduce the sources of confusion to the reader. Numbers are the most abstract of all: no-one can know the difference between 333 and 999 without an act of cognition (they both occupy a similar space). This is no mere trifle when one considers that complex tables may offer the readers thousands of numbers in a huge array. At least in bar charts different quantities are represented as bars of corresponding length—this allows the reader to handle the data more easily with perceptual mechanisms. At the same time, it follows (obviously) that nothing presents data so exactly as a number or a formula. Therefore we may presuppose that *no one graphic format will prove univer-*

sally superior Equally clearly, though some formats may be interchangeable, there are limits. Each format has its own domain of application, which may be well or poorly defined and which may overlap the domains of other formats to some extent. Ideally, we may hope for conceptual analysis, empirical research, and design experience to clarify such issues.

The Bar and Circle Controversy

Since the turn of the century many experts have given their opinion that bar charts are superior to circle charts and pie charts since the eye makes comparisons of *length* more easily and surely than comparisons of *area* or *volume* (Brinton, 1916, Karsten, 1923, and Neurath, 1936, are good examples). This was, maybe, a standing provocation to those of an empirical turn of mind to prove all the experts wrong. The first to succumb to this temptation was Walter Eells, whose paper in 1926 started half a century of controversy and confusion. The interesting curriculum survey by Mathews (also 1926) shows that the issue was indeed of importance to educators. Eells starts his paper with detailed quotes from the standard sources and then says:

> It is noticeable that all of the quotations given seem to be purely matters of opinion—none show any evidence of an experimental basis of fact. It is the object of this paper to report the method and conclusion of an experiment designed to test, by objective means, the validity of the criticisms expressed above. (Eells, 1926)

To do this, Eells drew some simple segmented bar charts and pie charts and asked students to "write in each sector their best estimate of the percentage of the whole represented by that sector." He found that his subjects could make such judgements "just as rapidly . . . with more accuracy" for the pie charts.

Six months later the same journal published an intelligent critique by Von Huhn of Eells' experimental technique. Von Huhn (1927) pointed out that Eells had used no scales on his charts—and it is easier to fit scales to bars than to pie charts; there were no labels on Eells' charts—and it is easier to fit labels onto bars than onto pie charts. Lastly, and I think decisively, Von Huhn also put his finger on the weakness of Eells' task criterion: one does not use segmented bars or pie charts for exact data—one uses them to show *comparisons*, for example, of totals at various times. Croxton added for good measure (1927, same issue) that the number of subjects and examples used by Eells was far too small. And I might add

that most of the expert advice mentioned by Eells referred to the superiority of single or grouped bars over circles: that is not the same thing as segmented bars versus pie charts.

After Von Huhn's analysis it should have been clear that Eells' experimental design was fatally flawed. Yet essentially the same questions were posed by Croxton and Stryker (1927), Peterson and Schramm (1955), and in a small part of Culbertson and Powers' work (1959). Their results tend to support Eells, but are open to the same counter-objections—inadequate stimulus material and inappropriate task criterion. True, we have not yet shown that the original advice was sound for the correct task, that is, making comparative judgements using bars and circles. Fortunately, the work of Croxton and Stein (1932) does just this. They tested the ability of 550 subjects to judge the relative size of bars, circles, squares, and cubes: "For each diagram the observers undertook to estimate the size of the smaller figure in relation to the larger one" (that is, a comparative task). Very large differences were found, entirely consistent with the textbook advice of Brinton and Karsten. We could hardly hope for a more conclusive demonstration that the choice of task was the crucial mistake made by Eells. The main conclusions of Croxton and Stein were:

- ☐ Comparisons based on bar charts were more accurate than comparisons based upon circles or squares.
- ☐ Comparisons based on circles or squares were more accurate than comparisons based on cubes.

Perhaps the contempt Eells felt towards practical communicators and his mistaken choice of task criterion are connected. If he really believed that the practical guides were "purely matters of opinion" then he would have no incentive to study the advice more carefully; and without studying the *art* of visual communication one cannot be sure that the question posed or the task chosen is at all meaningful. Actually, such men as Brinton and Neurath did not hold shallow, unsupported opinions. They were men of considerable intellect who understood what the scientific approach was all about. It is quite likely (certain in the case of Neurath) that informal trials of materials were held from time to time. Opinions based on experience and reason will, in general, prove more reliable than poorly designed experiments. The only weakness of such opinions is the scarcity of public evidence (documentation). Of course, from time to time, a "counter-

intuitive" experimental result *will* be found—a classic case is the design of aircraft attitude-indicators (Loucks, 1947). But if Polanyi is right, and scientific knowledge grows out of deep understanding of that which is studied (Polanyi, 1958, 1967) then such cases will always be the exception.

There the matter might well have rested were it not for some recent experiments by cartographers, especially by Flannery (1956, 1971) and Meihoefer (1969, 1973). Cartographers have long known that some of their favourite methods present readers with all kinds of difficulties—the example of Figure 20 (Bertin, 1967) is unfortunately only too typical. As Brinton showed so long ago (Figure 21) circles drawn on a linear (diameter) basis or on an area basis cause readers to misperceive the relative importance of the data.

If the misperception were systematic there would be the possibility of applying a *correction formula* to allow "psychologically correct" circles to be constructed. This is just what Flannery proposed, as also did Crawford (1969, 1971), Ekman and Junge (1961), Ekman, Lindman, and William-Olsson (1961), and Williams (1956). The essence of this work is that

FIGURE 20
Exact construction does not guarantee correct perception: A warning example from Bertin (1967)

the apparent and the actual values can be related by an exponent (apparent value = actual value raised to a constant power). The constants are reported to be:

0.80 (Williams)
0.86 (Ekman & Junge)
0.87 (Flannery)
0.91 (Crawford)

This is quite good agreement, considering all the problems that beset the researcher. Certainly, if it were not for Meihoefer (to whom we shall soon turn), one could settle happily for a working formula based on $V_A = V_R^{0.88}$. This, then is the summary of Flannery's work.

☐ Circles have certain practical advantages which make

FIGURE 21 *Brinton's explanation of the weakness of circle charts*

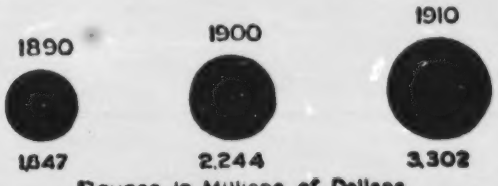
(a)

Figures in Millions of Dollars

Total Yearly Value for the United States of Combined Imports and Exports by Land and by Sea

In this illustration the data have been represented by circles drawn on a diameter basis. The right-hand circle appears more prominent than the data would justify. Circles compared on a diameter basis mislead the reader by causing him to over-estimate the ratios. Compare Fig. 38

(b)



Figures in Millions of Dollars

Total Yearly Value for the United States of Combined Imports and Exports by Land and by Sea

Here the data of Fig. 37 have been shown by means of circles drawn on an area basis, as recommended by many authorities on statistical work. The right-hand circle, however, shows up less prominently than the figures would justify. Circles compared on an area basis mislead the reader by causing him to underestimate the ratios. Circles of different size should never be compared. Horizontal bars have all the advantages of circles with none of the disadvantages

them popular—they can be placed on maps rapidly and don't take up as much space as bars.

- ☐ However, the relative values of circles are misperceived, and these mistakes are systematic. If quantity is related to area, readers tend to underestimate differences.
- ☐ Errors of perception can be minimised by applying a correction formula which (for area-based circles) has the form $V_A = V_R^{0.86}$ (in full $Y_t = 0.98365X^{(0.8747)}$ in which Y_t is the apparent relative size and X is the logarithm of the actual relative size).

Meihoefer's experiments on range-graded circles (that is, in stepped sizes) do seem to throw the idea of a correction formula into doubt (Meihoefer, 1969, 1973). He found that differences between area-based circles were indeed underestimated but that no correction formula could be derived from his data. This reviewer has not recalculated Meihoefer's results, but does note the great variability shown in his subjects' response charts. If it is true that the underestimation cannot be expressed in a systematic way, then of course the construction of a modified scale of sizes is a snare and a delusion. Nor does training seem to make much difference (Olson, 1970, 1975).

Since clearly we are dealing with a problem in psychophysics (the relation of absolute stimulus to perceived experience), maybe the data should be reanalysed for a fit with Weber or Fechner's Law or with Helson's adaptation-level formula. But Meihoefer has given us an altogether simpler solution. He has made the important discovery that errors in perception drop almost to zero if adequate scales are provided. Each step size used should be shown on the scale and (presumably, for it was not tested) the number of step sizes kept within reasonable bounds (Meihoefer used seven steps—probably close to the upper limit). The results were, as Meihoefer says, "so strikingly conclusive that statistical analysis of these tests would be redundant." So we see, in the end Von Huhn's comment about the lack of scales in Eells' experiment proved as sensible as all his other points—though we now know that scales can improve judgement of the relative values of bars *and* circles. At the time of writing this review, Meihoefer's work is the "state of the art" for representing data in circle form. His chief results were:

- ☐ Comparisons between range-graded circles based on area are underestimated but not in any systematic way.

- ☐ Errors can be reduced almost to zero by providing adequate scales. Continuous sizes should not be used; instead range-graded circles should be used with each step shown in the scale.

Fifty years on from Eells, where does the "bars versus circles" controversy stand? The Eells results on segmented bars and pie charts *were* confirmed by later work; but Von Huhn's criticisms still seem decisive. This suggests a pyrrhic victory for Eells: correct but irrelevant. Soon afterwards Croxton and Stein showed decisively that comparisons between pairs of bars could be made more accurately than between pairs of circles or squares or cubes. This was exactly what expert practitioners had been saying. They had never supported the use of segmented bars so strongly, because the segments lack a common axis or baseline for visual reference. Later, Meihoefer showed that circles could be used if they were range-graded and each step size shown in the key. On present evidence, grouped bars seem the safest bet with range-graded keyed circles and pie charts as possibilities, but we still know too little about pie charts to feel entirely comfortable at their widespread use. On this evidence continuous sized and unkeyed circles, segmented bars, and three-dimensional figures should not be used. The chief "competitors" to the bar and circle formats are (for professional readers) the data in tabular form and (for lay readers) pictorial charts of the Isotype format. These formats are discussed later.

Other Comparisons

Aside from the bar-graph/circle controversy there are only four sets of extensive tests of alternative methods of presentation. These are the work of Washburne (1927a, 1927b), Vernon (1946, 1950, 1951, 1952a, 1952b, 1953, and 1962) and the School of Agricultural Journalism at the University of Wisconsin (Culbertson & Powers, 1959; Culbertson, Flores, Powers, & Sarbaugh, 1959; Feliciano, Powers, & Kearl, 1962, 1963). The papers by Vernon are discussed in the section on pictorial charts; that leaves three substantial experiments to consider: Washburne, Culbertson and Powers, and Feliciano et al.

Washburne's experiment was impressive in scope and (with one reservation) sound in design. He presented a short account of the economic history of Florence to several thousand high school students. Data in alternative formats (prose, tables, pictographs, bars) were embedded in the story, and test questions covered both the storyline and the

data. His one mistake was to use a "bad system" pictograph (see section on pictorial charts). This poor stimulus material is in no way a fair test of the possible worth of pictorial charts, and thus all comparisons with this diagram have been discarded from my summary. Washburne's other conclusions seem to me amply justified (Washburne, 1927a, 1927b):

- ☐ The forms in which complex numerical data are presented make a decided difference in the resultant learning.
- ☐ Both the quantity and arrangement of data affect recall markedly and consistently.
- ☐ Both the logical and visual arrangement of data have an important effect upon learning.
- ☐ There is no form more effective in all respects than all other forms. Different formats and arrangements of data foster the learning of different types of facts.
- ☐ If memory of specific amounts is required, use a table with round numbers in numerical form ("5,000" not "5,422" or "five thousand").
- ☐ Never present numerical data in text form if there are more than one or two items to be presented.
- ☐ Use questions after the table or chart to emphasize its chief features.

Culbertson and his associates tackled the more specific question: "What characteristics of bar charts and line graphs make for ease or difficulty of learning?" Their experimental procedure is generally satisfactory, although once again substandard stimulus material almost puts in jeopardy otherwise sound work. Their chief conclusions are (Culbertson & Powers, 1959; Culbertson et al., 1959):

- ☐ Bar charts proved convincingly easier to read than line graphs.
- ☐ Grouped line graphs (each element originating from base line) were easier to read than segmented line graphs, which proved very difficult.
- ☐ The elements of bars and graphs should be labelled directly rather than indirectly by key or grid. Horizontal bars give room for labels and figures on or near the elements; this is the chief reason for preferring them to vertical bars.

Feliciano and her colleagues tested data presented as text, short and long tables, bar charts, and, finally, tables and charts supported by text. These experiments are soundly constructed and their conclusions can be accepted; the subjects were high school children and housewives, in other words, a

fairly unsophisticated general audience. The findings were (Feliciano et al., 1962, 1963):

- ☐ The mean scores for alternative formats were in this order: Horizontal bar charts > Short summary tables > Long detailed table > Text.
- ☐ The scores for bar charts and tables improved when supported by text. Thus the "best buy" (at least for this target audience—high school students and adult women) would be horizontal bar charts plus supporting text.

Graphs

There are virtually no experiments on the use of graphs in education, though a survey of national assessment tests in mathematics might give some basic information (for graph test items are included). As mentioned above, Culbertson and Powers (1959) found bar charts easier to read than graphs, and found segmented graphs more difficult still. Weintraub (1967) makes the good point that the skill of interpreting graphs must be learnt, and Price, Martuza, and Crouse (1974) draw our attention to the need for construct validity of test items in graphic tasks. Apart from this, we find no substantial work. Yet in many scientific subjects the interpretation of graphs is a vital part of the educational experience (see the excellent MacPherson and Jones, 1974, and also John, 1974). The question of *misrepresenting* data is mentioned in many texts (for example Moroney, 1951; Huff, 1967); such a theme is most vital when graphs are used to display social statistics.

Schutz (1961a, 1961b) provided two experiments on the use of graphs by engineers. Schutz (who used a defocussed 35mm slide display) chose judgement of *trends* as his task domain. This meant subjects had to extrapolate, interpolate, compare, and classify trends; they did not have to read out exact amounts. Schutz says "alpha-numeric displays do not facilitate this kind of task" and this, presumably, is why he compared the graphs with horizontal and vertical bars rather than tables. Even so, the task is clearly biased towards graph format, and the bar alternatives are substandard in quality. Thus his finding that the "line graph resulted in superior performance" is expected under the circumstances. It seems best to report Schutz's conclusion in permissive form:

- ☐ Line graphs can be used to show time-correlated data (trends).

In a second series of experiments, Schutz (1961b) investigated the sources of confusion that arise when multiple trend

lines are displayed on the same graph. He varied the number of lines, the coding of the lines, and the graph-reading tasks. Twenty-five kinds of black-and-white line codes were devised and the results presented as a 25 × 25 *confusion matrix* which shows for each code which other codes it was mistaken for. This allowed Schutz to select a submatrix of four codes no one of which was ever confused with the other three. The idea of conducting such tests to collect, classify, and summarise subject's errors is most important. It is a research technique natural to a working engineer, but all too seldom used by experimental psychologists (see Chapanis, Garner, & Morgan, 1949 and Chapanis, 1959, 1965, for a summary of such methods).

- ☐ Line-codes for graphs should be so chosen as to minimise confusion.

Once these optimal black-and-white line codes were identified the main set of experiments involved these variables: multiple line or multiple graph; two, three, or four lines; high and low confusion (extent of line crossovers); point-reading and comparing tasks; colour or black-and-white lines. These 48 fixed conditions (2 × 3 × 2 × 2 × 2) were tried out on ten subjects, who were professional engineers. The test session was self-paced, and the time taken for each item recorded. Under such conditions there were few errors, so the time taken was the chief measure of performance. These data when converted to logarithmic form and subjected to analysis of variance yielded these results:

- ☐ For reading points, multiple-lines and multiple graphs are equally good. But for comparison tasks the multiple-line display is always superior.
- ☐ In general, colour coding improved performance over the black-and-white code, especially for multiple-line graphs, but this effect was not of prime importance.

Tables The design and setting of tables is, to be sure, an arcane art which few have understood well. Yet primary source data obtained from social surveys are almost always presented in tabular form, and quite often modified or simplified versions of these tables are presented to the student or to the general public. Therefore, tables are one of the most important formats for presenting quantitative data. Tables are one of the most compact ways to present data and their only serious weakness is their abstract nature. Even quite sophisticated people need time to get the main points from a table (often

much more time than they would need with a bar chart or pictorial chart) and less educated people often cannot read tables at all. Thus the choice of table involves a complex trade-off between compactness, exactness, and ease of usage. Recent work by Ehrenberg has clarified our ideas on the design of tables for presenting social statistics (Ehrenberg, 1975, 1977; Chakrapani & Ehrenberg, 1976). His studies show that the design of tables can be markedly improved by a few simple principles (Examples are shown in Tables 1, 2, and 3):

- ☐ Round numbers to two significant digits: this facilitates mental arithmetic.
- ☐ Provide row and/or column averages: they are conceptual reference-points.
- ☐ Figures are easier to compare in columns; so use columns for the most important comparisons.
- ☐ Order rows and columns by size of numbers: and not, for example, by alphabetical order of the labels.
- ☐ Columns and rows should be compactly set, and not artificially "spaced out" to fit the page. Space can be used to distinguish relevant blocks of figures.
- ☐ Tables are the preferred format for the professional researcher or student of the social sciences. Ehrenberg's comparison between well designed tables and some mediocre bar charts and graphs is rather one-sided; still, tables are the obvious choice for the educated reader.

Ehrenberg's rules are supported by informal trials and some formal tests, by examples (one of which is shown here), and by a detailed discussion of the objections he has met in discussions with fellow scientists. For example, if two-digit rounding is criticised for "losing data", Ehrenberg defends by reminding us that much apparent precision is spurious, and that errors of rounding are in any case generally trivial in effect. Many people do understand the pointlessness of spurious precision, but often don't appreciate the *positive advantages* of eliminating the later digits: we can see, manipulate, and communicate two-digit numbers better (see the section "Seven chunks, or is it two?" in Simon, 1969). Ehrenberg's 1977 paper deserves reading for the way these issues are handled, and for the rare pleasure of reading an intelligent, literate paper on the practical art of presenting data.

Cartograms

Finally, there are some experiments on the particular graphic problems of cartograms. Areas of different value in choropleth maps have to be denoted by different colour, shade, or

TABLE 1 Unemployment in Great Britain

	1966	1968	1970	1973
Total unemployed (thousands)	330 9	549 4	582 2	597 9
Males	259 6	460 7	495 3	499 4
Females	71 3	88 8	86 9	98 5

Table from *Facts in Focus* (CSO, London, 1974, Table 97). As published, this table breaks most of Ehrenberg's rules.

TABLE 2 Unemployment in Great Britain

GB	Unemployed (000's)		
	Total	Male	Female
1973 (D)	600	500	99
'70 (B)	580	500	87
'68 (A)	550	460	89
'66 (C)	330	260	71
Average	520	430	86

The same data as Table 1 with rows and columns interchanged, numbers rounded and placed in decreasing order of size. Visual comparisons and mental arithmetic are now straightforward. The effect of these rearrangements is even more marked with larger tables.

TABLE 3 Unemployment in Great Britain

	Unemployed		
	Total	Male	Female
1973	600	500	99
'70	580	500	87
'68	550	460	89
66	330	260	71

The same data arranged to show the deleterious effect of artificial 'spacing out' to fit the page.

texture. Also, the information carried by the lines of an isopleth map can be reinforced by graded tones or colours applied to the areas. These cartographic possibilities have recently been investigated with some success.

The question of "grey scales" has been investigated by Jenks and Knos (1961). The idea of representing greater quantity by darker tone is quite old, and it is well known that equal increments of ink (percent area inked) do not produce the subjective perception of equal grades of darkness, a typical problem of psychophysics. Jenks and Knos' subjects compared five out of eight grey scales in detail (each of which relates perceived blackness to percent inked), finally choosing the Williams scale (Williams, 1956). But they do point out that the texture (size and arrangement of dots) causes some shades to appear "out of sequence" so cartographers must still take care even if they do use the Williams scale. The original paper is well worth reading for the discussion and examples, especially the scales and shaded pattern reference chart. The two main points are:

- ☐ When shades of grey are used to represent quantity an appropriate grey scale must be chosen to regulate the subjective perception. The Williams scale is recommended for general cartographic purposes.
- ☐ Ranking patterns by percent inked is not by itself sufficient: the texture of the grey can itself cause items to appear "out of order".

Colour is an important alternative for representing quantity on maps, but this reviewer has only found one experiment to date, that of Cuff (1973). Colour can be used quantitatively (e.g., weaker shades of red for areas of lower temperature) or qualitatively (e.g., strong red for high temperatures, strong blue for low temperatures, pale shades for intermediate areas). Cuff found that the qualitative scheme could be misread by subjects who assigned the lowest temperature to the lightest shade rather than the coolest colour. The quantitative scheme is definitely best, and shades can be selected by value and chroma score, though (of course) there are several colour scales to choose among. Cuff's conclusion is:

- ☐ To show values of one variable use a progression of darkness and intensity of one colour only.

Pictorial Charts

Pictorial charts use iconic symbols to show directly the subject of the visual argument being presented. Before considering the empirical research on pictorial charts it is worth seeing

how such charts are constructed. The chief authorities on this subject are Brinton (1916), Otto Neurath (1929, 1930, 1932, 1936, 1937a, 1937b, 1939, 1944a, 1944b), Marie Neurath (1965, 1973, 1974), Modley (1937), and Modley and Lowenstein (1952). Readers may be interested to know that the records of Otto Neurath's Isotype Institute have been donated to the archive section of the University of Reading Library (Reading, England), where they may be studied by accredited scholars.

The first step in designing pictorial charts is to organise the iconic symbols. Pictorial symbols should be self-explanatory and different from one another. The same symbols are used to represent the same things again and again: no variations just for the sake of it, nothing is changed unless there is a reason for changing. This rule (everything in the chart has a meaning, and any variations between charts also must have a meaning) leads on to the idea of a *visual grammar* or pictorial syntax. By this one does not mean "pictures in place of words". One means *rules whereby symbols can be articulated* (put together) *so as to present an argument in visual form.*

The second step is to decide how to represent quantity: one can either use *larger* symbols to show larger amounts or *more* symbols. The first of these alternatives has been regarded as a serious graphic mistake since the trenchant criticism by Brinton and Neurath. When larger quantity is represented by larger symbols several sources of possible confusion face the viewer. First of all, the viewer may think that the objects being represented have actually increased in size. For example, a larger house symbol would be read by some as "houses have been increasing in size", which is (as a matter of fact) the reverse of the truth. Then, a reader may realise the meaning but be misled by not knowing whether to look at the height, area, or volume of the symbols. Moreover, as we discussed before, the reader's perception of the relative areas or volumes may well be at odds with the measured dimensions. Remember, we continue to see distorted relationships even when we are cognitively aware of the true state of affairs.

Symbols of larger size can only say "this is greater than that". This is a rather poverty-stricken statement: it means we have turned a quantitative statement into a qualitative form. In an attempt to retrieve the situation designers often *put the original figures back into the diagram.* In this way they hope to recover some of the nuances of the original data, but actually this is an admission of defeat. It amounts to saying that quan-

titative data can be shown only by numbers and hence graphic art is reduced to external decoration. This is a conclusion which, in their different ways, academics and graphic designers are all too ready to reach.

The solution is astonishingly simple. The first step is to realise that the *larger quantity is represented by more figures of the same kind*. Brinton was the first person to make this clear (Figure 22). The second step is to *make clear what quantity or percentage each unit stands for*. So far as I know, Otto Neurath was the first person to appreciate this point; a close scrutiny of Brinton's work convinces me that he had not reached this stage at the time his great work was published. In an Isotype statement the numbers are contained within the symbols, which therefore have cognitive content as well as the attractive concreteness of iconic form (Figures 23 and 24).

Next comes the arrangement of symbols on the chart. To construct a visual argument some kind of comparison must be made, and usually an *explicit* comparison (before/after, here/there, this/that, etc.). Figure 25 is a typical example. Anything not crucial to the teaching point (to the visual comparison) must be left out. Visual language can have great force, but nothing destroys this impact more surely than unnecessary clutter. Here the words of Otto Neurath are worth noting:

He who knows best what to omit is the best teacher, and he who can omit nothing should not be a teacher at all . . . The Vienna school post-

FIGURE 22
The First Principle of Pictorial Charts (from Brinton, 1916)

Fig. 41. Number of Passengers Carried on the Railroads of the United States in 1899 and in 1911 Compared

Here is a chart drawn from the same data as Fig. 40. It was not a larger passenger, but more passengers, that the railroads carried. The ratio expressing increase in business can be clearly and accurately seen from this method of portraying the facts.

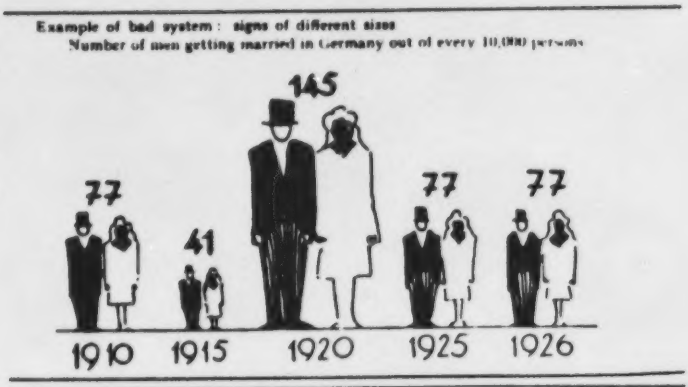


FIGURE 23
An example of "Bad System"—Signs of differing size used to show variations in quantity (from O. Neurath, 1936)

FIGURE 24
The same data as Figure 23 arranged as an isotype chart

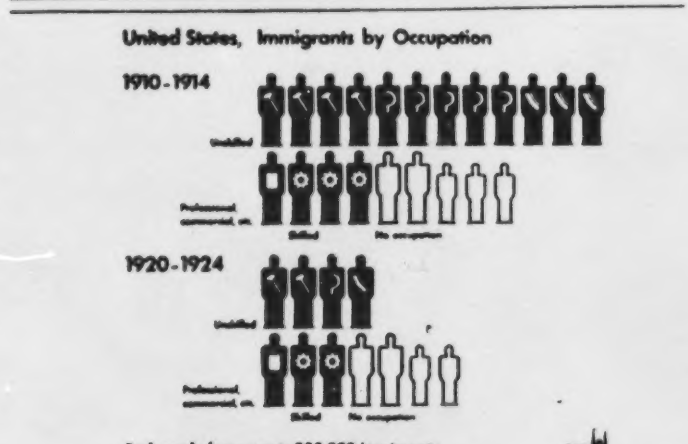


FIGURE 25
This isotype chart is a good example of the way visual comparisons can be put together to make a visual argument (Neurath & Neurath, 1939)

ulates: *to remember simplified pictures is better than to forget accurate figures*. (Neurath, 1925 [trans. 1973])

Our charts give as little detail as possible. In this they are the opposite of a naturalistic picture, and especially of a photograph . . . It is certainly not necessary for a chart to be poor in details, but all details must have teaching-value. (Neurath, 1936)

There is a great deal more to the art of pictorial charts than can possibly be discussed here. However, enough has been shown to give the reader some critical tools for assessing the worth of empirical studies. For example, Washburne (1927a) used pictorial charts which are classic examples of "bad system". We are quite entitled to reject this part of his work because of the poor stimulus material.

Far more influential is M. D. Vernon, whose work is still often quoted. Therefore, we must examine her work thoroughly—though (as it turns out) we shall learn more about the problems of the experimenter than we shall about the effectiveness of pictorial charts. Vernon's experiments were started in 1944 and were reported and summarised in a series of papers and popular accounts (Vernon, 1946, 1950, 1951, 1952a, 1952b, 1953, and 1962). Fortunately for this reviewer the style and content of this research did not change much during this time and the source paper (Vernon, 1946) can be regarded as typical of her work. We shall look at one series of tests which arose from the British government White Paper "Statistics Relating to the War Effort of the United Kingdom" (Great Britain, 1944).

In this White Paper occurred the data shown in Table 4. Vernon took these data and organised them in various formats:

1. as a table. No illustration of the table is given in any of her papers. Therefore we cannot know whether or not it was identical in setting to the table in the White Paper.
2. as a graph. Vernon gives no illustration for this graph.
3. as a histogram. It is not clear whether or not Vernon did construct a histogram for these data. Fortunately this is not crucial for this discussion.
4. as a pictorial chart (Figure 26).

These formats were presented to three groups of subjects: training college students, RAF crew, and a mixed army group. In the initial experiments subjects were asked to respond in their own words. In later experiments they were asked both specific and general questions. Both the details of

TABLE 4

These data from the White Paper "Statistics Relating to the War Effort" (HMSO, London, 1944) were used as the basis of some of Vernon's experiments.

NUMBER OF MALES AGED 14-64 IN GREAT BRITAIN

TABLE 1

Thousands

Mid-year	Armed Forces (1)	Whole-time Civil Defence	Industrial groups			Unemployed	Rest of male population (2)	Total male population aged 14-64
			Group I (3)	Group II (4)	Group III (5)			
1939 ...	477	80	2,600	4,688	5,798	1,043	1,324	16,010
1941 ...	3,271	324	3,140	4,264	116	158	704	15,977
1942 ...	3,785	304	3,285	4,154	3,553	103	750	15,934
1943 ...	4,284	253	3,305	4,040	3,093	76	870	15,921
1944 ...	4,502	275	3,210	4,039	2,900	71	943	15,910

(1) These figures, and also the total column, exclude prisoners and missing.
(2) Munitions industries, i.e., iron and steel, non-ferrous metals, shipbuilding, engineering, aircraft and vehicles, instruments, chemicals, explosives, etc.
(3) Agriculture, mining, National and Local Government, transport, shipping (including Merchant Navy), public utilities, food manufacture.
(4) Building, textiles, clothing, distribution, professional services, etc.
(5) Schoolboys, students, invalids (including war invalids), retired, etc.

experimental method and the results are (in my opinion) reported in a confused and unsatisfactory manner. This circumstance alone would be enough to make us rather cautious; it is by no means certain that Vernon's results are *reliable*. However, reliable or not, the main problem concerns the construct validity of the stimulus material used in these experiments.

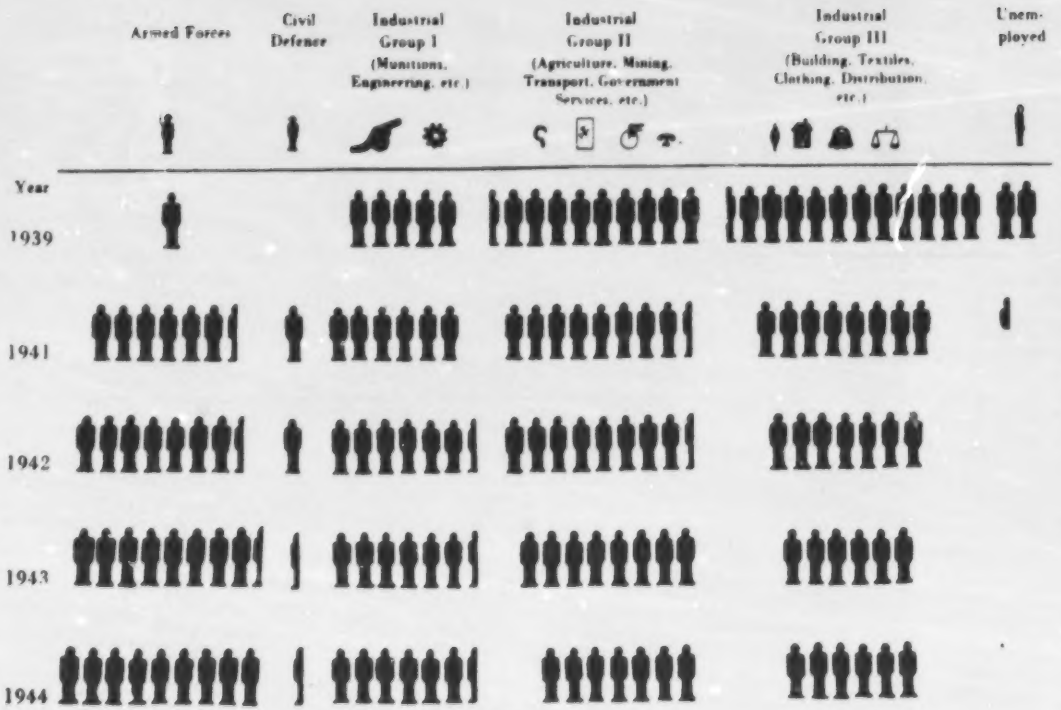
In Vernon's own words, the object of this work was "to undertake systematic enquiries into the understanding and remembering of information presented in such graphical forms" (Vernon, 1952a). Her main results with the White Paper data were: "Average scores . . . charts 47.3% correct; tables 47.2%; graphs 42.3%. This difference is not fully significant" (Vernon, 1946). On the other hand, judgements of difficulty did give some significant results (Table 5).

TABLE 5
Judgements of Difficulty (from Vernon, 1946)

	Percentage judging easiest			Percentage judging hardest		
	Charts	Graphs	Tables of figures	Charts	Graphs	Tables of figures
Army group	33	32	21	9	23	37
Airmen	35	43	13	17	17	37

FIGURE 26

Pictorial Chart Used by Vernon (1946)



Number of men aged 14-64 in Great Britain in various occupations

This pictorial chart was constructed from the data of Table 4 and used in the experiment described by Vernon (1946). According to M. Neurath, this example violates many of the basic principles of pictorial chart design.

Vernon summarised her work as follows:

> No all-round advantage is gained by using pictorial charts rather than graphs. The charts appeal more to the less educated individual while the graphs may intimidate him; but it is unlikely that he will understand the charts sufficiently well to make it worth using them. (Vernon, 1952a)

> As the author found in her inquiries, a mere study of the charts and perception of the pictorial shapes they showed was no guarantee that their meaning would be understood. Such understanding necessitates a reasonable intelligence and special training in how to interpret them. (Vernon, 1962)

Here, then, is a fair summary of Vernon's opinion: differences in presentation make little or no difference to the performance of subjects, and where subjects fail they fail because they are *not sufficiently intelligent or trained*. Substantiation of such a view would have dealt graphic communication a severe blow. After all, what is the point of such graphic systems as Isotype if indeed they cannot be read with greater facility than tables and graphs? Fortunately, we have to accept neither the no-difference result nor her explanation of why subjects fail.

There is a perfectly simple alternative explanation for Vernon's results, namely that the experiments were conducted with *incompetently designed graphic alternatives*. A test of a well-set table against a poor graph and a dreadful pictogram is invalid; you are not entitled to draw any general conclusions whatsoever. Moreover, when subjects fail is this because only bright, well trained people can understand pictograms? Or because it takes unusual intelligence to successfully unravel the visual confusion of a badly designed chart? Vernon's papers show the poor quality of her stimulus materials. Her graphs, histograms, and bar charts contain obvious, well known errors in design.

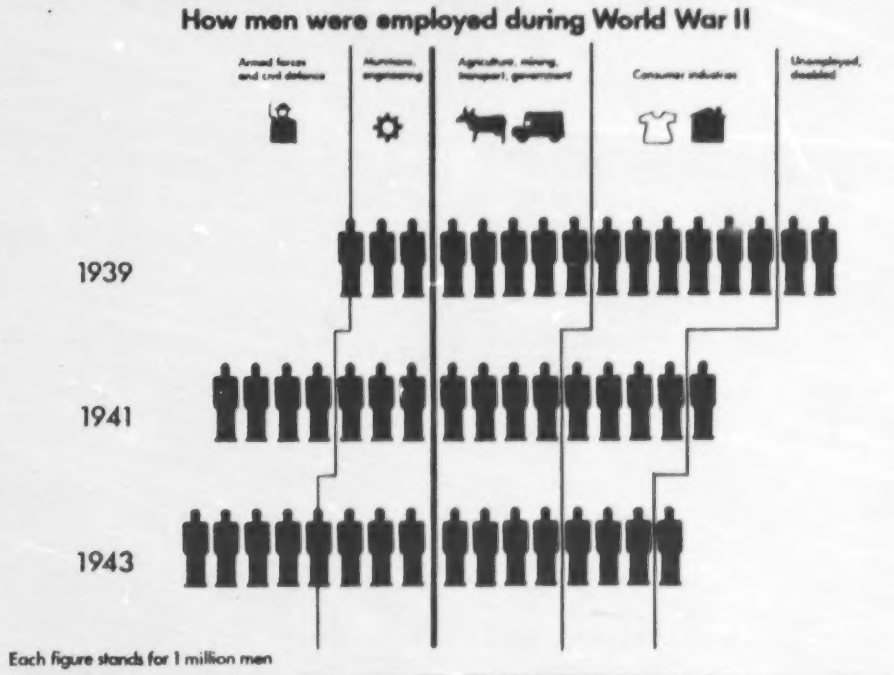
There is also good evidence that Vernon was ignorant of the principles of pictorial chart design. For a start, she nowhere mentions the key works of Brinton and Neurath, nor any of the textbooks that deal with pictograms (Brinton, 1916; Modley, 1937; Neurath, 1936). In her later reviews she uses the word "Isotype" but seems to mean by this nothing more than "groups of little men, etc." (Vernon, 1953, 1962).

The direct evidence comes from the diagram itself (Figure 26). All the groups are centered, so they tend to start and

finish in different places. This makes it difficult to compare the same group in different years. The groups in a single year are separated by varying amounts of space. This destroys the unity of each cohort (working men in one year) and makes it difficult to see that the total of men aged 14–64 remained the same throughout the war. The choice of 500,000 for the basic unit is poor; it gives an unnecessary number of symbols on the chart. Moreover, there is no need to show each year. The object is not to mimic the original table, but to construct a visual argument using the data originally supplied by the HMSO table. It is difficult to see what questions a subject might reasonably be expected to answer given Vernon's chart. Certainly, to attribute mistakes primarily to lack of intelligence or training is quite unreasonable.

Fortunately, it is possible for me to demonstrate how such a chart should be drawn and thus to show *one good way* a visual argument can be derived from the table. Marie Neurath has designed a genuine Isotype chart (Figure 27), and experi-

FIGURE 27
An Isotype Chart Designed by M. Neurath (also based on the data in Table 4)



ments are now under way to test its effectiveness. Most features of the chart are self-evident—the choice of a million men as the unit and the reduction to three key years clarifies the chart without losing any important information. The members of a cohort are *not* separated by space, thus retaining the basic unity of a group of men alive at a given time.

Only one feature of the Neurath chart needs further elucidation—the position of the main axis in the centre rather than on the left. Now, if the axis were on the left all the cohorts would align one under another; but the point which must be given priority is the shift from nonwar to wartime categories. Therefore, the axis is placed in the centre, with armed forces and munitions to the left and other occupations to the right.

This problem was discussed several times by Otto Neurath in terms like this:

> We might want to show that the rural population (each "O" representing 10 percent of the population) is decreasing and the urban population (each "X" representing 10 percent of the population) is increasing. Sometimes it may be sufficient to present this in the following way:
>
> 1920 OOOOOOOOXX
> 1930 OOOOOOOXXX
> 1940 OOOOOOXXXX
>
> But, if the point we want to stress is the change, then we may use a central "axis" and put it like this:
>
> 1920 OOOOOOOOXX
> 1930 OOOOOOOXXX
> 1940 OOOOOOXXXX
>
> The two presentations are equivalent numerically, but not visually. (O. Neurath, 1944)

Other aspects of the Vernon papers are also unsatisfactory. For instance, IQ tests are reported on two groups labelled "secondary education" and "primary education only"; yet in a later paper these *same results* are ascribed to "with grammar school education" and "without grammar school education" (Vernon, 1946, 1952a). Of course, these two descriptions have entirely different meaning. If we cannot even rely upon the way IQ results are reported then our suspicion of other, more central, parts of this work must be reinforced. It seems clear that the Vernon experiments do not support the conclusions she drew from them.

At least one experimenter, Wrightstone (1936), has used good quality pictorial charts (designed by Rudolf Modley) for his tests. He found such charts were generally superior to other formats; in particular:

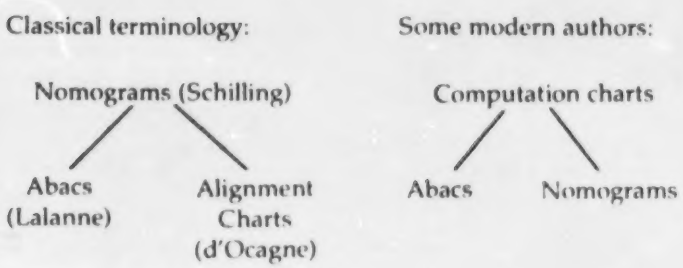
- ☐ Pictorial charts were superior for locating and interpreting facts and for delayed recall.
- ☐ Other formats were better for immediate recall.
- ☐ Pictorial charts were thought to be more interesting than alternative formats.

The half-century of experience with Isotype charts has shown that they are intelligible and interesting to the general reader. They do take skill and time to design well, and the reader does need some practice to learn the visual conventions. Pictorial charts are not necessary or suitable if the target audience is composed of professional social scientists; for that kind of educated readership tables are the preferred format.

PART II PRESENTING EXACT NUMBERS

Exact numerical data are usually presented in a table (for example logarithm tables) or a nomogram (which allows users to read the value of a complex function off a graph or set of scales). To decide on a format one must look at the complex trade-off between bulk, convenience, and use. Such trade-offs have not been investigated in depth; the decisions made result from the accumulated years of experience of many practising scientists. Often (as with log tables) one may use different versions for different purposes. It is certain that there is no "universal" solution in such cases: it all depends on the user's purpose, i.e., the task in view.

Nomograms are in everyday use by engineers and other scientists, yet they have previously been ignored by the literature of instructional technology. A few words of explanation may help clear up some possible difficulties. The term *nomogram* can be used broadly to mean a graphic representation of a formula or narrowly to mean the alignment charts invented by d'Ocagne. The reason is historical; originally all charts for calculation were plotted on Cartesian co-ordinates and were called "abacs" by Lalanne (1842). D'Ocagne's alignment charts opened up new vistas and are claimed by many to be greatly superior to the older abacs (see, for instance, comments in Griffin, 1932). Thus some authors have reserved nomogram to mark d'Ocagne's charts; others keep the more general usage recommended by Schilling (1900).



This review keeps to the classic usage, that is, a nomogram is a graphic representation of an equation on a plane surface. The subcategory "abacs" helps remind us that these are not quite the same as those graphs which display trends and relationships for general information. Graphs are tools of education while abacs are tools of action. Admittedly, there are examples that can serve both functions, but the distinction is useful. The design of any graphic form (and of any experiments to test its effectiveness) are constrained by its purpose, that is, by the way it is meant to be used.

The literature on nomograms is in a fairly satisfactory state. For reference there is the famous d'Ocagne (1899) whose book ran through many reprints and editions and influenced the whole development of the subject. Allcock and Jones (1932), Davis (1962), Douglass and Adams (1947), Ford (1944), and Levens (1948) are the standard works in English. Griffin (1932) gives a list of important references, and Carroll (1960) and Moffat (1965) cover some of the basic ground. Funkhouser (1937) on the history of the subject is another useful source.

The experiments on nomograms are designed by people who are clearly familiar from personal experience with the principles of their construction and use. This (and the relative clarity of the subjects' tasks) has led to some of the most exemplary work this reviewer has found in his survey. Of course, a review of this kind tends to concentrate attention on those experiments which have been reported *in extenso* in the journals of education and psychology. But in a practical field of endeavour like nomography there may well be a thousand field trials for every one reported; it would be a great mistake to think that human knowledge is limited to reports of experiments published in journals! Nevertheless, *well designed* experiments can help to clarify key issues for the practising communicator.

Data may be presented for operational use as a set of tables or as a nomogram. This question was investigated by Carter (1946a, 1946b; 1947) with results that tended to favour the use of tables. In passing he also showed why abacs must be distinguished from other kinds of graph.

> All of the tables and graphs represented the function $Y = X^2/C$ where $C = 60, 70, 80, 90$ and $100 \ldots$ it should be clearly understood that the conclusions apply only to tables and graphs which are being used as a method of presenting functional relationships where it is desired to find the answer to a given argument. The results should *not* be extrapolated to graphs which are being used to demonstrate the general shape of a function, points of inflection, points of maxima and minima, etc. (Carter, 1947)

Precisely. This is exactly the kind of distinction to which we must be sensitive. Carter found that his results held for both linear and nonlinear curves and for both single curves and families of curves. His main conclusions were:

- ☐ Where accuracy is paramount then an explicit table containing every point needed is superior to simpler tables and to graphs.
- ☐ Graphs with more rulings are not read more accurately than graphs with fewer rulings.
- ☐ It makes no difference whether the graph is entered on the x or the y axis.
- ☐ Graphs should not be used to present data unless the shape of the curve is important or unless speed and accuracy of use are relatively unimportant.

It seems these conclusions are justified, though the last recommendation needs some qualification. The function chosen by Carter ($Y = X^2/C$) is a relatively simple one, yet even so the most detailed table ran to 12 pages. With more complex functions or with a series of functions the tabular material might fill a small volume; such tables may be expensive to produce or impractical in use (an engineer may work in the field where books are cumbersome and computer terminals nonexistent). In such cases a set of nomograms on a clipboard may be the only practical tool. Moreover, the shape of a curve *is* often a vital source of information, and is instantly accessible to the trained eye. So the overall balance between tables and nomograms is unlikely to be as much in favour of tables as Carter's work might suggest at first reading.

The work of Beeby and Taylor (1973) is quite exemplary, and is not a bit the worse for their evident unawareness of the

previous research on graphs and nomograms! They worked to produce a series of design charts for the British *Code of Practice for the Structural Use of Concrete* (CP110:1972). The first chart is shown in Figure 28; designers use such charts to find out how much reinforcing steel is required in a reinforced concrete beam. The possible sources of error when using this chart are:

a. in reading the initial bending moment;
b. in finding the correct point on the vertical axis;
c. in lining across to the graph line;
d. in selecting the correct graph line;
e. in lining down to the horizontal axis;
f. in reading the value of the required steel area from the horizontal axis;
g. in writing this figure down.

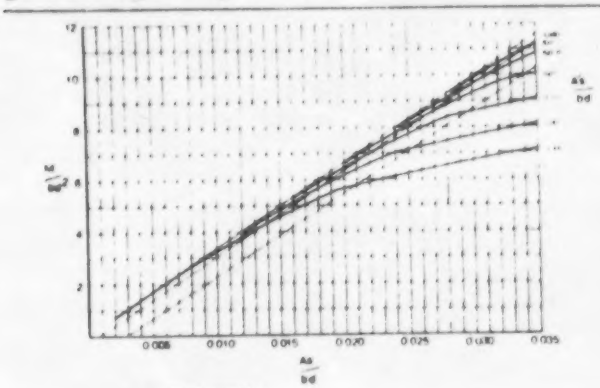


FIGURE 28
The First Abac Designed by Beeby and Taylor (1973)

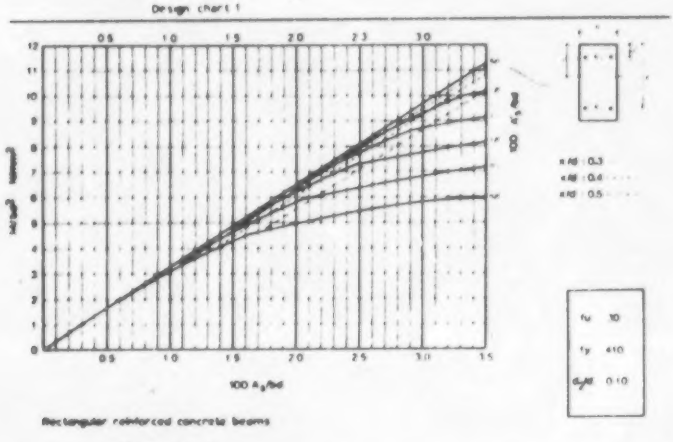


FIGURE 29
The Second Version of Beeby and Taylor's Abac

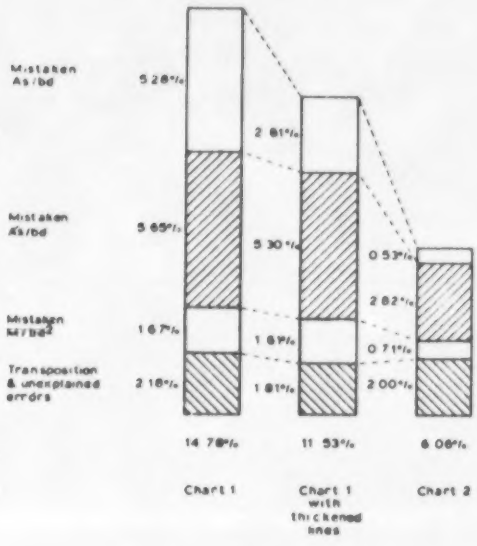
In the first series of tests (with professional men on a training course) Beeby and Taylor found that most errors were clearly caused by one or more particular features of the chart:

> One persistent error was in misreading the scale on the vertical axis. In the first chart alternate lines only are numbered . . . many people read the unnumbered lines as halves, for example, they read 7 as 6.5. A second source of error was in using the wrong A's/bd line. People persistently lost track of the zeros in front of the number and read, for example, 0.0025 as 0.025. The other source of error we could recognise was in misreading the As/bd axis by one or more squares. Thickening the main lines reduced these errors considerably. Finally, there were errors that we could not interpret; these might be due to mistakes in reading or writing down figures. (Beeby & Taylor, 1973)

The second chart (Figure 29) was designed to take care of the identified errors. This new chart was tested on another batch of engineers with good results; the distribution of errors in the two tests is shown in Figure 30.

Beeby and Taylor then conducted a third series of tests to get more general data on the basic operations involved in

FIGURE 30
Error Analysis by Beeby and Taylor (1973)



Summary of mistakes made in using the three versions of beam design charts

chart-reading. These tests led to the following design rules:

- ☐ The grid size should be as large as possible. Small grid sizes allow greater accuracy but also increase the likelihood of making mistakes. If a grid spacing of less than 10 mm is used, some lines must be thickened.
- ☐ Axes should be numbered in the range $0.1 \leq N \leq 100$. Numbers outside this range tend to confuse. The best system of numbering is to have each line of the grid numbered 1, 2, 3, etc. Increments of 2 or 0.5 are acceptable; increments of 0.25 should not be used.
- ☐ If the graph is read y axis → curve → x axis then the curves should make an angle with the x axis of 30° or more.
- ☐ The following relationship predicts the accuracy with which a result from a chart can be expected.

$$S = \sqrt{\left[(S_y \cot \theta)^2 + 2 S_x^2 + 1.5 S_z^2 \right]}$$

S is the standard deviation (SD) of the answer about the correct answer, S_y and S_x are the SD expected in reading off y and x axes, S_z is the SD expected in interpolating between lines on the chart and θ is the angle between the x axis and the tangent to the curve at that point ($\tan^{-1} dy/dx$).

These results of Beeby and Taylor are strikingly close to the sensible advice given by Chapanis et al. (1949, Ch. 6). Again the methods used are just as important as the results: the procedures of engineering design (human engineering) have shown themselves to be at least as appropriate as the more familiar methods of laboratory psychologists. In particular, the collection and analysis of errors seems to be a most fruitful tool.

Most nomograms can be designed in abac or in alignment chart form, and in the literature there are many references to these alternatives. For example, Griffin (1932) describes the following as "a striking contrast in ease of reading a nomogram [= alignment chart] over an abac". (See Figures 31 and 32, next two pages.)

This is a classic example of the "criticism, alternatives and tests" model first proposed by Macdonald-Ross and Waller (1975b) in their short review of research into typography. This reviewer has not so far found any records of empirical tests on such alternatives, though we may be sure that many informal trials must have been held. The general opinion is that an alignment chart is easier to use and leads to fewer mistakes

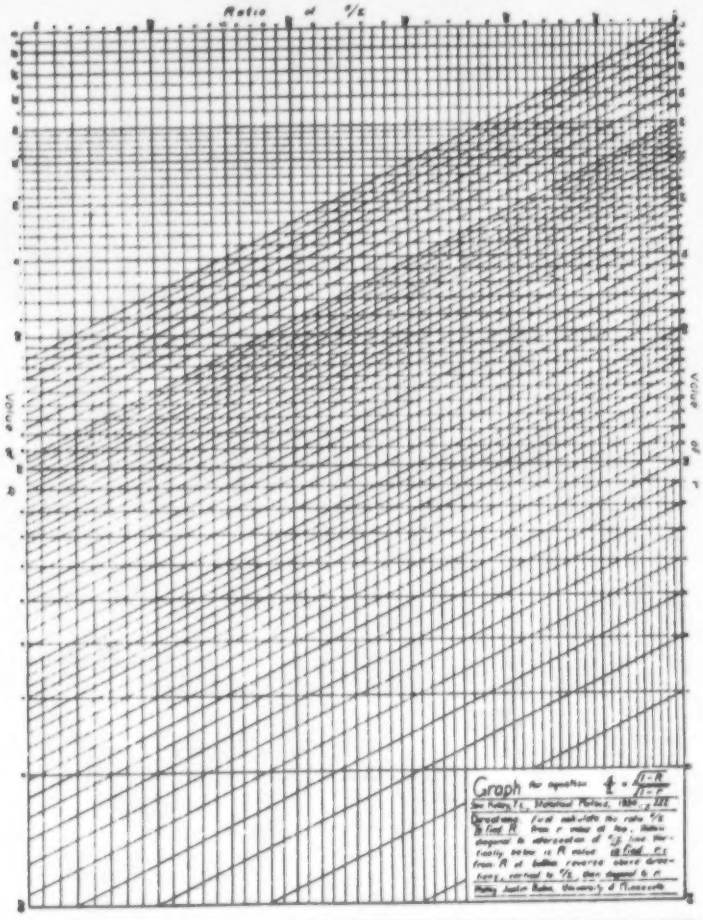
than an abac. Such a widespread opinion among engineers and scientists is likely to be based, at least, on a good deal of practical experience.

Exact numerical data can also be presented in *tables*, when Ehrenberg's principles (given earlier) usually still hold good, except that operational tables (such as logarithms, chi-tests, etc.) cannot adhere to the "two significant digits" rule.

There are a few experiments on the design of tables for presenting exact numerical data, though not by any means

FIGURE 31
An Abac for Estimating Reliability (from Rulon, 1930)

Graph for Estimating Reliability



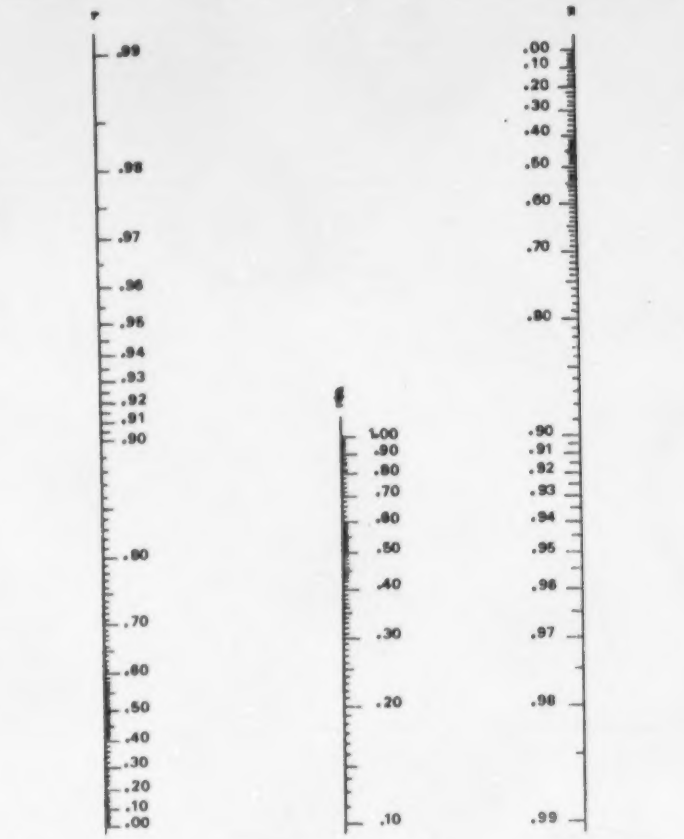


FIGURE 32
An Alignment Chart for Estimating Reliability (based on the same formula as Figure 31; from Cureton & Dunlop, 1929)

sufficient for the needs of the practising typographer. The experiments by Wright (1968, 1972, 1973) and Wright and Fox (1970) on decimal currency tables bring out the important distinction between *explicit* tables (where the information can be read directly) and *implicit* tables (where the user must extrapolate or add figures to get the solution). The chief result was:

> If the user of a table is required to carry out operations other than *search* and *read*, the number of competent users is markedly reduced. Tabulation schemes requiring synthetic or analytic operations by the user seem to buy economy of space at the cost of comprehension. (Wright, 1973)

Wright also found that her tables were used more quickly if so arranged that subjects scanned vertically rather than horizontally (this is Ehrenberg's third rule). It is safe to agree with Wright that the spacial arrangement of rows and columns, the headings chosen and the size, character, and colour of the print are all significant variables. Wright's views on the relation between laboratory experiments and field trials are also well worth noting:

> The lesson to be drawn is that as working conditions become poorer so there is an increasing advantage for the easier table . . . . Small differences found between tabulation formats used by very bright people tend to become large differences when the tables are used by people of lesser ability . . . it is all too easy for intelligent people, looking at a particular table in conditions of comparative calm, to feel that variations in display have only marginal effects; but in the working environment there can be substantial benefits from using the easier of two typographic formats. (Wright, 1973)

For good measure we can add the rather neat experiments by Hartley and his colleagues who tested the effect of typing tables in centered and ranged-left forms (Hartley & Young, 1975). They found typists took twice as long to produce the centered tables and made 25 percent more errors. As my colleague Robert Waller points out, this finding applies to headings but not to the numbers which must always range right to show the order of magnitude (decimal place):

197	197
63	63
1201	1201
correct setting	incorrect setting

So, to summarise these few experiments on tables:

- ☐ The logical, spacial, and typographic organisation of a table makes a good deal of difference to the user.
- ☐ Explicit tables should be preferred wherever possible.
- ☐ When tables are typed, both headings and columns should range left.

Finally, we should note that cartograms can be used as a source of exact information for geological or engineering purposes. Seen in this light the contours on a map are part of a typical trade-off situation in which the available data, the scale and content of the map, and the user's needs have to be balanced against each other. Merriam and Sneath (1966) dis-

cussed some of the statistical problems but empirical studies in this field are still hard to find.

SUMMARY Many issues that interest practical communicators have never been investigated. For example, no one has looked at the trade-off between time and cost of construction and resultant educational benefit. This shows the distance between researchers and designers, for every design studio must have faced the choice between a simple but uninspired format (such as bar charts) and a stimulating format that is difficult to execute well (such as Isotype). Actually, few experiments are done in a "working environment". Formative evaluation is rare; most tests were conducted on material produced by the researcher himself—and how that shows!

Nevertheless, some of these experiments did address important questions and produce reliable and useful results (listed in this paper). In general, the advice given by the best practical communicators has been substantially vindicated. One or two workers quite openly suggested that such advice was just "a matter of opinion" and hence as likely to be wrong as right. The body of research reviewed here does not bear out this view. On the contrary: there is no known case where a well articulated and deeply held practical viewpoint has been overturned, and many cases where the practitioner has been upheld.

The way numerical data are presented does matter to the learner. Washburne (1927a) said, "Both the logical and visual arrangement of data have an important effect upon learning". Wright (1973) said, "The logical, spacial and typographic organisation of a table make a good deal of difference to the user". We are not concerned here with small, marginal differences; the object of the most ambitious graphic communicators (such as Neurath) is to make difficult ideas accessible to the whole of the community. This they may do by the art of teaching, (selecting and arranging the material to be shown), and by their graphic ability. This graphic ability is shown by their choice of the correct format for a particular purpose and by the detailed execution of the chosen format. The experimental research tells us that such efforts can substantially help the learner to understand the message or to complete the task.

No one graphic format is universally superior to all others, though some are so unsatisfactory that they can be virtually

discarded from the armoury. To choose the best format for a particular occasion one must decide: what kind of data is to be shown? What teaching point needs to be made? What will the learner do with the data? Can previous models be copied? Do we have the time and skills to execute the format? Some formats require much knowledge and practice to get good results (some maps, nomograms, Isotype). Other formats are simpler, though it is surprising to see what errors can be invented by authors or illustrators. It pays to remember that graphic communication is an *art*, that is, a skill which results from knowledge and practice.

This review separated the research work first according to the purpose of the communication. If the reader was meant to look at general aspects of the data then the criterion tasks ought to involve comparisons or trends or differences. If the reader needed exact numbers then those numbers would be used in some operational task. This proved to be a useful separation which allowed the reviewer to avoid some confusions found in the earlier literature. On the other hand one must admit that some charts or maps can be used for both purposes; indeed map theorists do tend to make more use of the general-purpose/special-purpose dimension.

Some of the specific results are worth repeating here. Of the abstract formats (those needing words to identify the subject-matter) horizontal bars often proved a good choice, and were better than graphs or tables for a general audience. Obviously graphs and tables have their place for the professional reader and for particular subject matters. On the other hand, segmented graphs and three-dimensional forms (that represent quantity by volume) should *never* be used. The position of circles, pie charts, and segmented bars is equivocal. It seems that unkeyed circles of different sizes should never be used; but range-graded circles can be used on maps if and only if each step is shown on the scale. Segmented bars do save space, but lose the common reference line. They should only be used as a last resort. Little is known about pie charts. Some ask the reader to make many fine judgements of angle: this is obviously silly. But this reviewer has seen some imaginative uses of pie charts, and recommends a "not proven" verdict for the moment. As always, a great deal depends upon the artfulness of the illustrator.

Otto Neurath's Isotype system comes through this review unscathed. This is one of the great graphic inventions of the

century. It needs more skill than many think at first glance: some who believe they understand Isotype demonstrate the contrary as soon as they stick the "little men" onto paper. Nevertheless, anyone who hopes to be a graphic communicator must master the theory and practice of this system. Because Vernon did not do so her work on this subject should be put to one side.

All these formats work best when accompanied by text. The text should not just repeat points made by the chart: it should direct, comment, explain, and question. Thus text-plus-chart is the usual teaching apparatus, as one or two researchers have realised.

Exact numbers can be shown in tables or by nomogram. This is a classic "trade-off": there may be a best answer for each particular case but there is no general advantage for either format. These categories are, anyway, quite gross; they need a good deal of dissection before any general principles can be discerned. Nomograms are divided into abacs (Cartesian graphs) and alignment charts. For complex equations alignment charts are decidedly easier to use.

Most of the experimental designs are to some extent inadequate. Sometimes this reviewer has felt that it would be hard to build in more obstacles to valid interpretation. Experiments take time and cost money; 20 or 30 years may go by before another worker looks again at similar problems. Therefore, why not spend that extra effort at the design stage?

With three or four exceptions, *all* the work reported here was done with substandard stimulus material. In some cases the charts were so poor that no reasonable person could use the results. What conclusions can be drawn if a badly designed chart fails to communicate? None! With the intermediate cases a fairly relaxed stance seemed appropriate: the stimulus material was assumed to be adequate unless any of the basic principles of design of that format were flagrantly violated.

Several workers asked their subjects to carry out tasks which were not appropriate to the purpose of the communication or the nature of the stimulus material. Usually this meant they asked for rote recall of exact numbers. Admittedly, this makes it easy to score the responses—but it is difficult to imagine such questions being asked in a natural educational setting. Moreover, many of the formats (such as bar charts or Isotype) are naturally adapted for visual *compari-*

sons, and would hardly be chosen if rote recall of exact numbers was the intention.

All too often the published reports contain insufficient detail for a sound critical assessment. For example, some workers published no examples of the stimulus material; others reported the results in ordinary language only, with no numerical data! With the best will in the world one cannot give such reports as much weight as perhaps they might deserve. Finally, there were various "technical" defects, for example, in the statistical analysis of the data. Nowadays young researchers get extensive training in data handling, and indeed the later papers do show sounder statistical technique.

On the positive side we should look for more attention to the purpose of the graphic device, better quality stimulus material, and better definition of the target audience. The first paragraph of this review stresses the importance of selection and purpose; but this idea must not be read too simply. Extreme subjectivism is not permissible: the expert must first be clear about what might legitimately be said before selecting the particular message. Also, some messages are more selective than others—the expert may deliberately offer data which can be used in more than one way. We do need researchers and communicators to think more carefully about the reader. The difference between a professional reader and a lay reader; the difference between a reader familiar with the graphic format and one who is not—these are critical issues which need more description and analysis. The old behaviourist slogan, "what will the reader *do* with the information?" lacks subtlety, but points in the right direction.

The idea of the *master performer* is worth reviving. This notion (which was well known in task-analysis/programed-learning circles) captures one great truth: most of the expertise in any practical art resides in people rather than on paper. This is a reminder for those who tend to assume that all knowledge is recorded on paper (with, of course, empirical test data). On the contrary, most human know-how resides in people, and one of the first tasks of the researcher is to find ways and means of *externalising the know-how*. No one will ever produce good stimulus material without mastering the art of those formats, and no one can master the art from printed sources alone. What is more, the researcher will soon discover that most practitioners are more or less incompetent! The only way through is to identify the master performers.

The idea of *error analysis* is also fruitful. It is not possible to predict all the pitfalls, so even well produced materials may contain the seeds of misinterpretation. Most errors are meaningful; that is, they are systematic mistakes caused by features of the stimulus or by misconceptions held by the subjects. The virtue of error analysis is that it usually shows *how* the material has to be changed so as to reduce the error rate.

In general, the kind of research needed on meaningful learning material is related to the style of ergonomics or operational research. Macdonald-Ross and Waller (1975a, 1975b; 1976) looked at the research into typography and developed a model for research that is certainly just as appropriate here. In their view the tacit know-how of expert communicators must be linked to the process of empirical testing. This is done by a three-part cycle of *criticism, alternatives,* and *tests.* The empirical investigations are always conducted on coherent alternatives which make use of articulated criticism. The object of the criticism is to externalise some of the hitherto tacit know-how demonstrated by master performers. As we have developed this model we have noticed how often designers don't see the need for formal tests, and how often psychologists think our concern for the quality of the test material is some peculiar personal idiosyncracy! To our eyes this mutual lack of understanding is one reason why progress in graphic communication has been so slow and uncertain. Yet there has indeed been some progress as this review has shown.

REFERENCES

Allcock, H. J., & Jones, J. R. *The nomogram.* New York: Pitman, 1932.

Beeby, A. W., & Taylor, H. P. J. How well can we use graphs? *Communicator of Scientific and Technical Information,* 1973, *17,* 7–11.

Bertin, J. *Semiologie graphique: Les diagrammes, les reseaux, les cartes.* Paris: Mouton Gauthier Villars, 1967.

Brinton, W. C. *Graphic methods of presenting facts.* New York: Engineering Magazine, 1916.

Cajori, F. *A history of mathematics.* New York: Macmillan, 1894.

Cajori, F. *A history of mathematical notations* (2 vols.). LaSalle, Ill.: Open Court, 1928.

Carroll, P. *How to chart data.* New York: McGraw-Hill, 1960.

Carter, L. F. *The relative effectiveness of presenting numerical data by the use of tables and graphs* (Memorandum Report No. TSEAA 694–1). HQ Air Material Command, Engineering Division, April 17, 1946. (a)

Carter, L. F. *A study of the best design of tables and graphs for presenting*

numerical data (Memorandum Report No. ISEAA 694-1C). Wright-Patterson Air Force Base, OH: Aero Medical Laboratory Engineering Division, 1946. (b)

Carter, L. F. An experiment on the design of tables and graphs used for presenting numerical data. *Journal of Applied Psychology*, 1947, *31*, 640–650.

Chapanis, A. *Research techniques in human engineering*. Baltimore: Johns Hopkins University Press, 1959.

Chapanis, A. *Man-machine engineering*. Belmont, CA: Wadsworth, 1965.

Chapanis, A., Garner, W. R., & Morgan, C. T. *Applied experimental psychology: Human factors in engineering design*. New York: Wiley, 1949.

Chaprakani, T. K., & Ehrenberg, A. S. C. *Numerical information processing*. London: London Business School, 1976.

Coombs, C. H. *A theory of data*. New York: Wiley, 1964.

Crawford, P. V. *Visual properties of uniform grey-tone point symbols and line symbols used in graduated series on maps*. Unpublished doctoral dissertation, University of Kansas, 1969.

Crawford, P. V. Perception of grey-tone symbols. *Annals of the Association of American Geographers*, 1971, *61*, 721–735.

Croxton, F. E. Further studies in the graphic use of circles and bars. *Journal of the American Statistical Association*, 1927, *22*, 36–39.

Croxton, F. E., & Stein, H. Graphic comparison by bars, squares, circles and cubes. *Journal of the American Statistical Association*, 1932, *27*, 54–60.

Croxton, F. E., & Stryker, R. E. Bar charts versus circle diagrams. *Journal of the American Statistical Association*, 1927, *22*, 473–482.

Cuff, D. J. Colour on temperature maps. *Cartographic Journal*, 1973, *10*, 17–21.

Culbertson, H. M., Flores, T., Powers, R., & Sarbaugh, L. E. *Using graphs more effectively for economic information* (Bulletin 29). University of Wisconsin: Department of Agricultural Journalism, 1959.

Culbertson, H. M., & Powers, R. D. A study of graph comprehension difficulties. *AV Communication Review*, 1959, *7*, 97–100.

Cureton, E. E., & Dunlap, J. W. A nomograph for estimating the reliability of a test in one range of talent when its reliability is known in another range. *Journal of Educational Psychology*, 1929, *20*, 537–538.

Dantzig, T. *Number: The language of science*. New York: Macmillan, 1939.

Davis, D. S. *Nomography and empirical equations* (2nd ed.). New York: Reinhold, 1962.

D'Ocagne, M. *Traite de nomographie*. Paris: Gauthier-Villars, 1899.

Douglass, R. D., & Adams, D. P. *Elements of nomography*. New York: McGraw-Hill, 1947.

Eells, W. C. The relative merits of circles and bars for representing

component parts. *Journal of the American Statistical Association*, 1926, *21*, 119–132.

Ehrenberg, A. S. C. *Data reduction*. New York: Wiley, 1975.

Ehrenberg, A. S. C. Rudiments of numeracy. *Journal of the Royal Statistical Society*, in press, *140* (Series A).

Ekman, G., & Junge, K. Psychophysical relations in visual perception of lengths, area and volume. *Scandinavian Journal of Psychology*, 1961, *2*, 1–10.

Ekman, G., Lindman, R., & William-Olsson, W. A psychological study of cartographic symbols. *Perceptual and Motor Skills*, 1961, *13*, 355–368.

Feliciano, G. D., Powers, R. D., and Kearl, B. E. *Text table or graphs for communicating statistical information* (Bulletin 32). University of Wisconsin: Department of Agricultural Journalism, 1962.

Feliciano, G. D., Powers, R. D., & Kearl, B. E. The presentation of statistical information. *AV Communication Review*, 1963, *11*, 32–39.

Flannery, J. J. *The graduated circle: A description, analysis and evaluation of a quantitative map symbol*. Doctoral dissertation, University of Wisconsin, 1956.

Flannery, J. J. The relative effectiveness of some common graduated point symbols in the presentation of quantitative data. *Canadian Cartographer*, 1971, *8*, 96–109.

Ford, L. R. *Alignment charts*. Notre Dame, Ind.: Notre Dame Press, 1944.

Funkhouser, H. G. Historical development of the graphical representation of statistical data. *Osiris*, 1937, *3*, 269–404.

Great Britain Prime Minister's Office. *Statistics relating to the war effort of the United Kingdom* (HMSO Command Paper 6564). London: Prime Minister's Office, 1944.

Griffin, H. D. How to construct a nomogram. *Journal of Educational Psychology*, 1932, *23*, 561–577.

Hartley, J., & Young, M. On the typing of tables. *Applied Ergonomics*, 1975, *6*, 39–42.

Hogben, L. *From cave painting to comic strip*. London: Max Parrish, 1949.

Hogben, L. *Mathematics in the making*. London: Macdonald, 1960.

Huff, D. *How to lie with statistics*. London: Gollancz, 1967.

Jenks, C. F., & Knos, D. S. The use of shading patterns in graded series. *Annals of the Association of American Geographers*, 1961, *51*, 316–334.

John, V. B. *Understanding phase diagrams*. New York: Macmillan, 1974

Karsten, K. G. *Charts and graphs: An introduction to graphic methods in the control and analysis of statistics*. Englewood Cliffs, NJ: Prentice-Hall, 1923.

Kendall, M. G., & Buckland, W. R. *A dictionary of statistical terms*. Edinburgh: Oliver and Boyd, 1957.

Lalanne, L. L. C. *Anamorphose logarithmique*. Paris: 1842.

Levens, A. S. *Nomography*. New York: Wiley, 1948.

Lorenz, K. Z. *Studies in animal and human behavior*. London: Methuen, 1971.

Loucks, R. B. An experimental evaluation of the interpretability of various types of aircraft altitude indicators. In P. M. Fitts (Ed.), *Psychological research on equipment design*. Washington, D.C.: Government Printing Office, 1947.

Macdonald-Ross, M. *Graphics in text. Review of Research in Education*, in press.

Macdonald-Ross, M., & Smith, E. *Graphics in text: A bibliography*. Great Britain: Open University, Institute of Educational Technology, 1977.

Macdonald-Ross, M., & Waller, R. *Open University texts. Criticisms and alternatives*. Great Britain: Open University, Institute of Educational Technology, 1975. (a)

Macdonald-Ross, M., & Waller, R. Criticism, alternatives and tests. A conceptual framework for improving typography. *Programmed Learning and Educational Technology*, 1975, *12*, 75–83. (b)

Macdonald-Ross, M., & Waller, R. The transformer. *Penrose Annual*, 1976, *69*, 141–152.

MacPherson, I. S., & Jones, B. R. *The interpretation of graphs in physics*. London: Hutchinson, 1974.

Mathews, C. O. *The grade placement of curriculum materials in the social studies*. New York: Columbia University, Teachers College Press, 1926.

Methoefer, H. J. The utility of the circle as an effective cartographic symbol. *Canadian Cartographer*, 1969, *6*, 105–117.

Methoefer, H. J. The visual perception of the circle in thematic maps: Experimental results. *Canadian Cartographer*, 1973, *10*, 63–84.

Merriam, D. F., & Sneath, P. H. A. Quantitative comparison of contour maps. *Journal of Geophysical Research*, 1966, *71*, 1105–1115.

Midonick, H. *The treasury of mathematics*. (2 Vols.). London: Penguin, 1968.

Modley, R. *How to use pictorial statistics*. New York: Harper, 1937.

Modley, R., & Lowenstein, D. *Pictographs and graphs: How to make and use them*. New York: Harper, 1952.

Moffat, D. *Charts and nomographs for electronic technicians and engineers*. Blue Ridge Summit, PA: TAB Books, 1965.

Monkhouse, F. J., & Wilkinson, H. R. *Maps and diagrams: Their compilation and construction* (3rd rev. ed.). London: Methuen, 1971.

Moroney, M. J. *Facts from figures*. London: Penguin, 1951.

Neurath, M. *Living with one another*. Macdonald, 1965.

Neurath, M. *Otto Neurath and isotype*. (Japan): Graphic Design, 1973.

Neurath, M. Isotype. *Instructional science*, 1974, *3*, 127–150.

Neurath, O. Gesellschafts-und Wirtschaftmuseum in Wien. Wien: Osterreichische Geneinde-Zeitung 2 Jahrung no. 16, 1925. Translated and reprinted in M. Neurath & R. S. Cohen (Eds.), *Empiricism and sociology*. Boston: Reidel, 1973.

Neurath, O. *Die bunte welt: Mengenbilder fur die jugend*. Wien: Artur Wolf, 1929.

Neurath, O. *Gesellschaft und wirtschaft*. Leipzig: Bibliographisches Institut, 1930.

Neurath, O. *Technik und menschcit*. Wien-Leipzig: Deutscher Verlag fur Jugend und Volk, 1932.

Neurath, O. *International picture language*. London: Kegan Paul, 1936.

Neurath, O. *Basic by isotype*. London: Kegan Paul, 1937. (a)

Neurath, O. Visual representation of architectural problems. *Architectural Record*, July 1937, 57–61. (b)

Neurath, O. The human approach to visual education. *Health Education Journal*, 1944, *2*, 61–66. (a)

Neurath, O. Visual aids and arguing. *New Era*, 1944, *25*, 51–61. (b)

Neurath, O., & Neurath, M. *Modern man in the making*. New York: Knopf, 1939.

Olson, J. M. *The effects of class interval systems on the visual correlation of chloropleth maps*. Doctoral dissertation, University of Wisconsin, 1970.

Olson, J. M. Experience and the improvement of cartographic communication. *Cartographic Journal*, 1975, *12*, 94–108.

Peterson, L. V., & Schramm, W. How accurately are different kinds of graphs read? *AV Communication Review*, 1955, *2*, 178–189.

Polanyi, M. *Personal knowledge*. London: Routledge & Kegan Paul, 1958.

Polanyi, M. *The tacit dimension*. London: Routledge & Kegan Paul, 1967.

Price, J. R., Martuza, V. R., & Crouse, J. H. Construct validity of test items measuring acquisition of information from line graphs. *Journal of Educational Psychology*, 1974, *66*, 152–156.

Robinson, A. H., & Sale, R. D. *Elements of cartography* (3rd ed.). New York: Wiley, 1969.

Rulon, P. J. A graph for estimating reliability in one range knowing it in another. *Journal of Educational Psychology*, 1930, *21*, 140–142.

Schilling, F. *Uber die Nomographie von M. d'Ocagne*. Leipzig: Teubner, 1900.

Schutz, H. G. An evaluation of formats for graphic trend displays. *Human Factors*, 1961, *3*, 99–107. (a)

Schutz, H. G. An evaluation of methods for presentation of graphic multiple trends. *Human Factors*, 1961, *3*, 108–119. (b)

Simon, H. *The sciences of the artificial*. Cambridge, MA: M.I.T. Press, 1969.

Smith, D. E. *History of mathematics* (2 vols.). New York: Dover, 1958.

Smith, D. E., & Ginsburg, J. *Numbers and numerals*. New York: Columbia University, Teachers College Press, 1937.

Smith, D. E., & Karpinski, L. C. *The Hindu-Arabic numerals*. Boston: Ginn, 1911.

Torgerson, W. S. *Theory and methods of scaling*. New York: Wiley, 1958.

Tukey, J. W. *Exploratory data analysis*. Reading, MA: Addison-Wesley, 1976.

Vernon, M. D. Learning from graphical material. *British Journal of Psychology*, 1946, *36*, 145–158.

Vernon, M. D. The visual presentation of factual material. *British Journal of Educational Psychology*, 1950, *20*, 174–185.

Vernon, M. D. Learning and understanding. *Quarterly Journal of Experimental Psychology*, 1951, *3*, 19–23.

Vernon, M. D. The use and value of graphical material in presenting quantitative data. *Occupational Psychology*, 1952, *26*, 22–34. (a)

Vernon, M. D. The use and value of graphical materials with a written text. *Occupational Psychology*, 1952, *26*, 96–100. (b)

Vernon, M. D. Presenting information in diagrams. *AV Communication Review*, 1953, *1*, 147–158.

Vernon, M. D. *The psychology of perception*. London: Penguin, 1962.

Von Huhn. Further studies in graphic use of circles and bars: A discussion of the Eells experiment. *Journal of the American Statistical Association*, 1927, *22*, 31–36.

Washburne, J. N. An experimental study of various graphic, tabular and textual methods of presenting quantitative material. Part I: *Journal of Educational Psychology*, 1927, *18*, 361–376. (a)

Washburne, J. N. An experimental study of various graphic, tabular and textual methods of presenting quantitative material. Part II: Numerals and written numbers. *Journal of Educational Psychology*, 1927, *18*, 465–476. (b)

Weintraub, S. What research says to the reading teacher: Reading graphs, charts and diagrams. *Reading Teacher*, 1967, *20*, 345–349.

Williams, R. L. *Statistical symbols for maps: Their design and relative values* (Contract NR 008–006 Nonr 609 (03)). Washington, D.C.: Office of Naval Research, 1956.

Wright, P. Using tabulated information. *Ergonomics*, 1968, *11*, 331–343.

Wright, P. Explicit and implicit tabulation formats. *Ergonomics*, 1972, *15*, 175–187.

Wright, P. Understanding tabular displays. In Ergonomics Research Society & The Society for Industrial Artists and Designers, *The visual presentation of technical data*. Great Britain: University of Reading Typography Unit, 1973.

Wright, P. Presenting technical information: A survey of research findings. *Instructional Science*, 1977, *6*, 93–134.

Wright, P. & Fox K. Presenting information in tables. *Applied Ergonomics*, 1970, *1*, 234–242.

Wrightstone, J. W. Conventional versus pictorial graphs. *Progressive Education*, 1936, *13*, 460–462.

Zeisel, H. *Say it with figures*. New York: Harper, 1947.